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THE UNIVERSITY OF ALBERTA

RECLAMATION STUDIES OF A SALINE-SODIC SOIL

by



HENRICUS S. A. Vander PLUYM, B.Sc.

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Reclamation studies of a saline-sodic soil" submitted by Henricus S. A. Vander Pluym, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Over the years the Maple Creek "V" irrigation project area became highly saline as a result of natural seepage from the surrounding sandhills and through improper irrigation practices. To reclaim the area conventional methods were introduced. Proper drainage was installed, border dikes and basins constructed, and natural reclamation was allowed to take its time.

This study was initiated to compare the reclamation achieved by the border dike and by the basin type of irrigation. The rates and uniformities of reclamation by the two methods were determined and compared. In the laboratory permeability and swelling tests were conducted. Soils and leachates were analyzed. From these tests it was hoped to develop an artificial chemical method of reclamation, which would speed up the rehabilitation of the project, and as a result render the reclamation more economically feasible. Finally, cost and benefit analyses of the reclamation methods were made.

From the permeability and swelling tests, the "threshold" and "jump-off" concentrations, respectively, were found, which delineated the "area of stable permeability". Through the economic study the leachants and their respective application periods were selected, which would render the highest net profit.

The economic study proved that the most economical leachants for reclamation had concentrations lower than depicted by the "area of stable permeability". This was in contrast with the hypothesis; that the "area of stable permeability" might cover the concentrations of

the most economical leachants. Simultaneously, it proved that the concentrations for these leachants were amply supplied by the well water. Consequently, the rate of the artificial reclamation was similar to that of natural reclamation.

Nevertheless, the \$130/hectare profit indicated that immediate artificial reclamation should be considered as an integral part of any rehabilitation program for salinized irrigated areas.

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INTRODUCTION

During the 1930's southwestern Saskatchewan suffered acutely from drought and the economic depression of that decade. In order to assist farmers by providing a reliable source of feed for stock the P.F.R.A. assisted with the establishment of many small irrigation schemes in the area. One of the P.F.R.A. projects was called the Maple Creek "V" irrigation project.

Figure 1 shows the "V" projects located approximately 64 kilometers north of the Cypress Hills and 32 kilometers east of the Alberta-Saskatchewan border. The area of the "V" projects totals 650 irrigable hectares, 340 of which are privately owned, the Crown having title to the remaining. The Upper "V" (Figure 2) containing 250 irrigable hectares is located in sections 4 and 9, township 14, range 26, west of the third meridian. The Lower "V" (Figure 3) with 400 irrigable hectares is located in sections 23, 24, 25, and 26 of township 14, range 25, west of the third meridian.

At the present time the Upper and Lower "V" projects are both strongly affected by salts. This resulted from a continuous process of ponding and evaporation of seepage water carrying small concentrations of salt from the higher surrounding areas. Improper irrigation practices, as well as seepage from canals, Lee Lake, and the neighbouring sand hills, and the presence of an artesian aquifer beneath the projects resulted in accelerated salinization of both areas (Milne and Rapp, 1966).

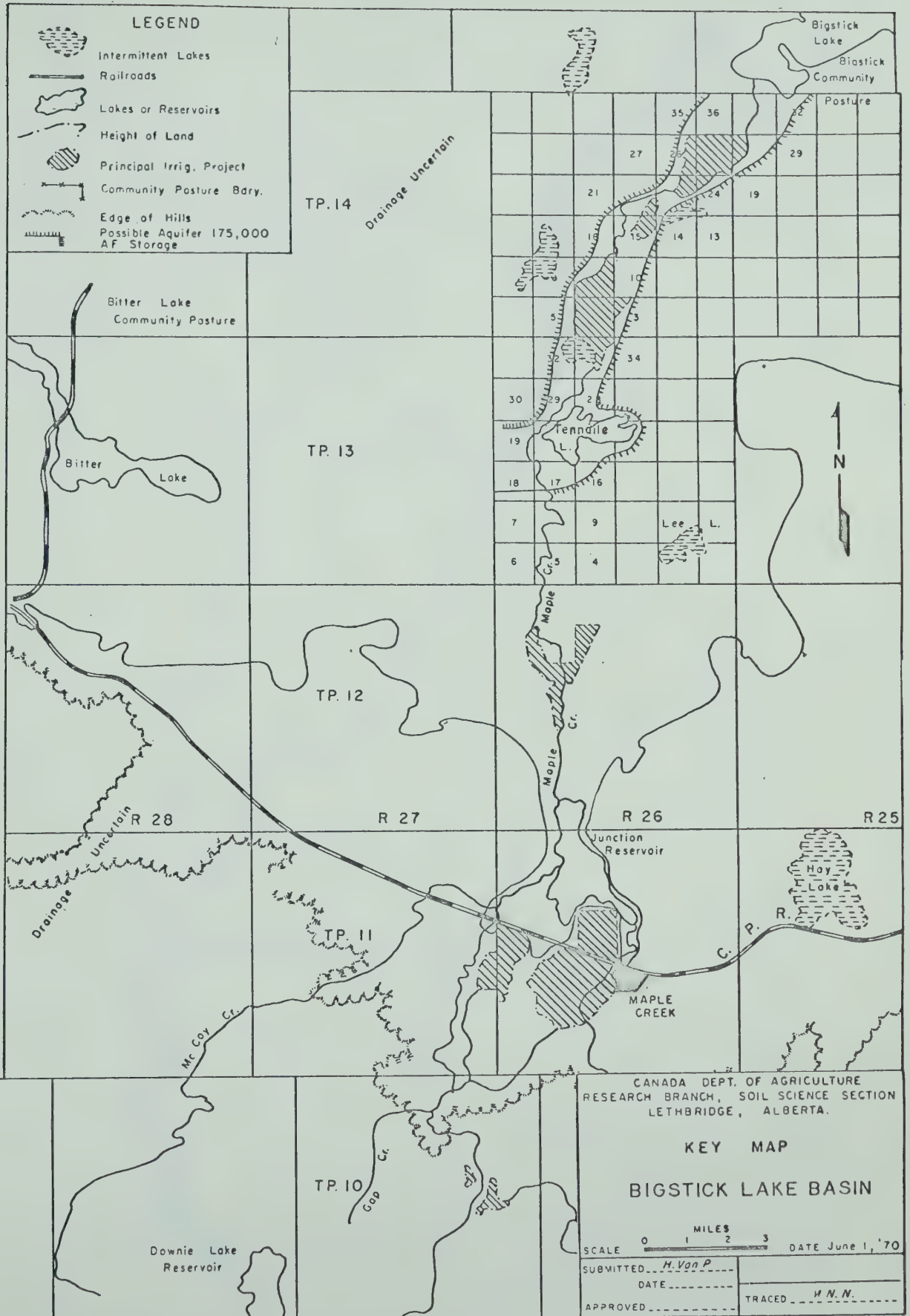


Figure 1. Map showing location of principal Maple Creek irrigation projects in southwestern Saskatchewan.

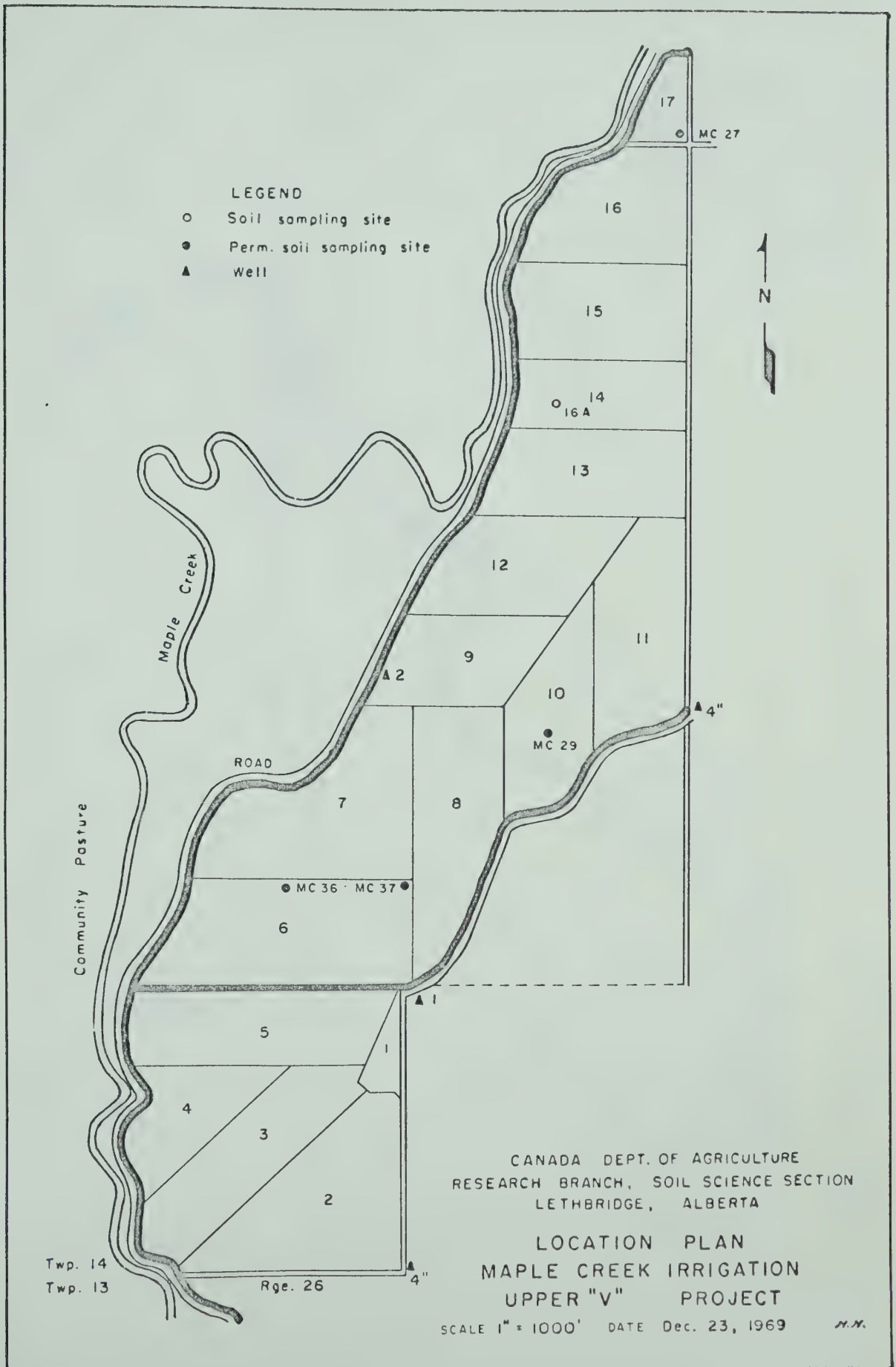


Figure 2. Map showing details of the Upper "V" irrigation project.

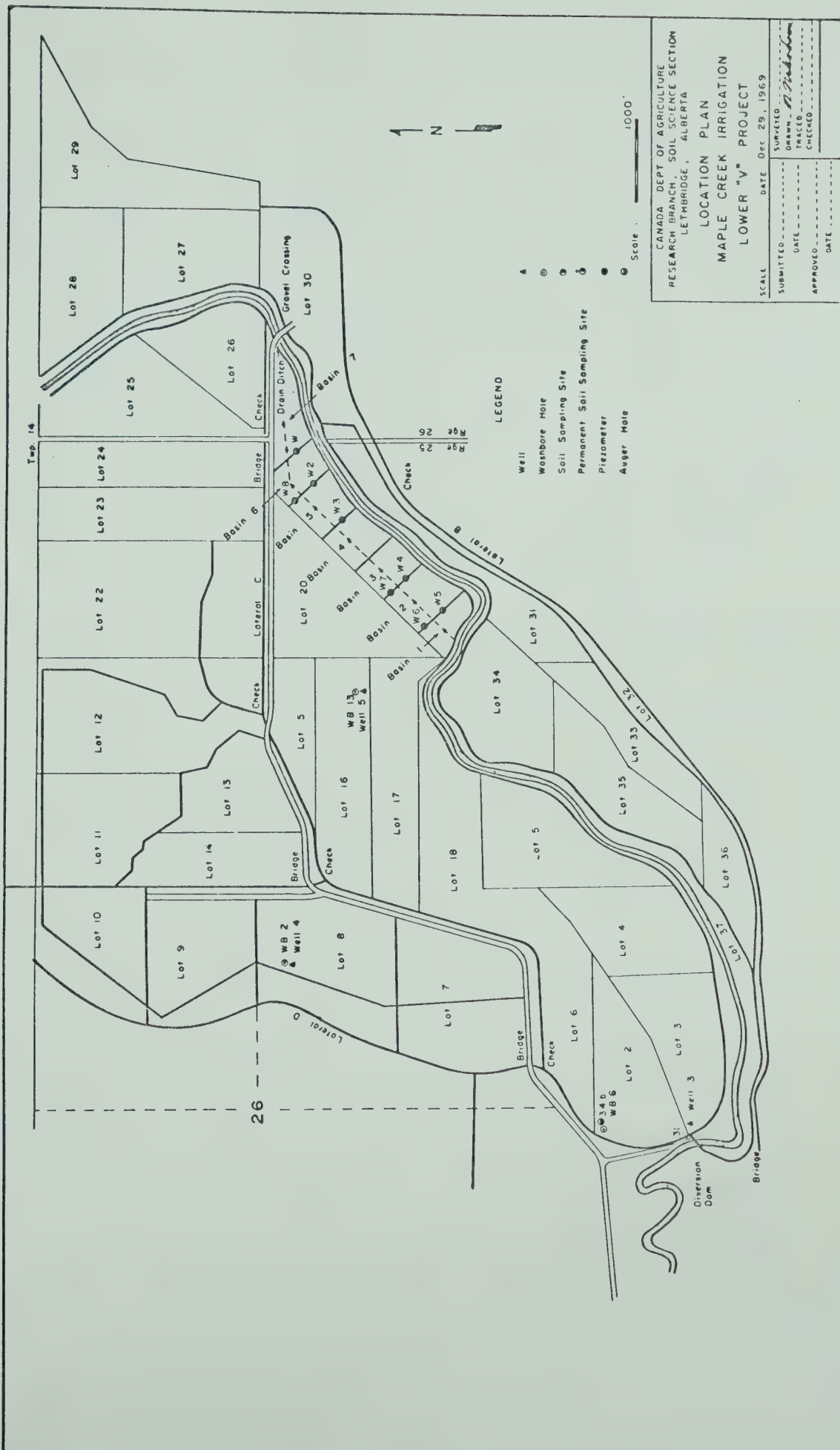


Figure 3. Map showing details of the Lower "V" irrigation project.

By 1948 the "V" projects were already so unproductive as a consequence of salinization that extensive reclamation efforts were commenced. The costly work involved was deemed justifiable because knowledge gained should be applicable in other parts of the region. As part of the scheme to reclaim the two salinized projects, deep well pumps, which extended into the aquifer, were installed. They were intended to lower the watertable as well as to provide supplemental irrigation water. The water obtained by pumping was highly saline (1,500 ppm), which proved to be beneficial to the reclamation of saline-sodic soils by the high-salt-water-dilution method. Reeve and Doering (1966b) contended that a highly concentrated leaching solution could serve as a flocculant and as a source of divalent cations during the early stages of reclamation. The high content of electrolytes would cause a flocculation of the soil colloids and consequently improve the permeability of the soil. On the other hand the divalent cations would replace the sodium ions on the soil complex and so maintain the favorable permeability during the final stages of the reclamation when the salt concentrations of the leachants would drop again.

Good results were obtained in the Upper "V" project as a result of the high-salt-water-dilution method of reclamation. Milne and Rapp (1966) reported that over a 2-year period substantial reductions in electrical conductivity (EC) (from 17 to 13 mmhos/cm) and of sodium adsorption ratio (SAR) (from 39 to 23) had been obtained. However, it was not known whether or not maximum efficiency had been attained in the existing reclamation schemes on the "V" projects.

This was because the so-called "area of stable permeability" (Quirk and Schofield, 1955), which indicates the concentrations and SAR's giving a maximum permeability, was unknown for this soil. In addition no proper attention had been given to the economic aspects of reclamation. Therefore, simulated reclamation schemes, all starting from different levels of salinity and done with various solutions, were set up along with swelling tests in order to determine the so-called "area of stable permeability". Subsequently, the most economical scheme of reclamation and its endpoint were selected by means of a cost and benefit analysis.

Specifically the objectives of this study were:

- (1) To evaluate the rate and uniformity of reclamation achieved since inauguration of the work in 1951,
- (2) To determine the so-called "jump-off" and "threshold" concentrations of the saline leaching solutions for this particular soil, in order to outline the "area of stable permeability",
- (3) To evaluate and compare various amendments for effectiveness and cost,
- (4) To estimate crop returns and reclamation costs for different levels of salinization of this particular soil, and
- (5) To compare the rate and extent of existing reclamation schemes on the "V" projects to those of the simulated laboratory reclamation schemes.

LITERATURE REVIEW

The reclamation of saline irrigated soils is a complicated matter, much influenced by many factors. Therefore this literature review is subdivided into several sub-sections so as to more conveniently discuss some of the relevant aspects of such work. Because this report is concerned with the high-salt-water-dilution method of reclamation, hydraulic conductivity, and economic considerations, the review will be primarily concerned with factors relevant to these aspects.

Classification of Salt-Affected Soils

Reclamation methods for salt-affected soils must be ones suited to the characteristics of the soils concerned. According to the United States Salinity Laboratory Staff (1954), salt-affected soils can be placed in a utilitarian classification scheme consisting of three categories.

- (1) Saline soils -- whose saturation extracts have EC (Electric Conductivity) values of 4 mmhos/cm or greater, ESP (Exchangeable Sodium Percentage) values of less than 15, and whose pH is usually less than 8.5.
- (2) Saline-sodic soils -- whose saturation extracts have EC values of 4 mmhos/cm or greater and ESP values greater than 15, the pH being less than 8.5.
- (3) Non-saline-sodic soils -- which have saturation extract EC values

less than 4 mmhos/cm, ESP values greater than 15, and a pH above 8.5.

There are some other systems of classifying saline soils. In the taxonomic classification of Canadian soils, saline soils are designated by the adjective "saline" while sodic soils, with strongly developed solonetzic B horizons and Ca/Na ratios of less than 10, are classified under the Solonetzic order. However, most soils in the small irrigation projects of southwestern Saskatchewan are classified as saline Regosols. The 7th Approximation identifies saline soils with the adjective "hal-" or by the great group name Salorthids, while sodic soils are given the syllable "natr-" in their great group names.

The High-Salt-Water Dilution Method of Soil Reclamation

One very successful method for amelioration of saline-sodic soils is leaching, employing what has been called the "high-salt-water dilution" method. The leaching process is commenced employing a solution so saline that a high rate of permeability is attained. After rapid permeability has been established, the leaching solution is simultaneously diluted in concentration and enriched with Ca-salts. Dilution of the leachant permits the removal of excess salt in the soil solution. At the same time dilution increases the activity of the Ca ions already present in the leachant, while addition of Ca amendments increases the Ca ion activity to an even greater extent. The result is replacement of Na ions adsorbed on the exchange complex by Ca from the leaching

solution. Removal of the Na in the leachate then leads to improved aggregate stability and soil permeability.

1. The effect of high-salt-water upon permeability

Success of the high-salt-water method for reclaiming saline-sodic soils depends on the ability of salt in the leaching solution to influence hydraulic conductivity. Electrolytes affect the swelling and flocculation of clays and so have an indirect influence on permeability. When the electrolyte content of a leaching solution increases the swelling of clays decreases and as a result permeability increases. Because swelling increases the thickness of the oriented water films in the micro and macro pores, it also increases the amount of micropore space at the expense of the macropores, the ones primarily responsible for permeability. McNeal (1968) and Lagerwerf et al. (1969) reported the relationship between swelling and hydraulic conductivity in equations. According to McNeal the hydraulic conductivity (K) is related to the swelling factor (X) as follows:

$$1 - K = \frac{CX^n}{1 + CX^n}$$

where C and n are constants. Lagerwerf et al. suggested that K is related to the so-called "effective porosity" ($E - \Delta E$), which is the difference between the total pore volume (E) and the swelling value (ΔE). A special section of this review will be devoted to literature on clay swelling. For the time being, it is shown that a decrease in salt content will indirectly result in a decrease of hydraulic conductivity.

Quirk and Schofield (1955) proposed in a quite arbitrary manner that a 15 per cent reduction in hydraulic conductivity as compared to the hydraulic conductivity of the soil after it was first equilibrated with the high-salt-solution, is the maximum reduction in permeability which is practically permissible during the reclamation of a salt affected soil. Rowell et al. (1969) termed the salt concentration in a leaching solution which limits the decrease in hydraulic conductivity to 15 per cent, the "threshold" concentration. However, even during the initial equilibration with the high-salt-water there is already a 20 to 30 per cent reduction in hydraulic conductivity because of the water-potential difference between the dry soil and the advancing waterfront and also because of compaction and re-allocation of soil particles, and the presence of air bubbles, all of which obstruct the conducting pores (Doering, 1965). In addition, when a soil is being leached, a temporary impediment may form in the lower parts of a soil due to accumulation of illuviated exchangeable sodium (Reeve and Doering, 1966). Thus, although not all permeability decreases can be prevented, excessive reductions in hydraulic conductivity in soils of high ESP values can be averted if there is a high electrolyte concentration in the leaching solution.

2. Subsequent leachings with diluted-high-salt solutions

After stable permeability has been established, as a result of high-salt-water leachings, the next step in the high-salt-water-dilution method is to decrease the EC and the ESP of the leaching

solution. Doering and Reeve (1965) proposed doing this by leaching the soil with dilutions of the high-salt-water to which calcium salts had been added.

In order to decrease the electrical conductivity of the soil being treated, the salts in the soil solution have to be leached out. The movement of moisture out of the soil will carry with it salts previously in the soil and the soil solution. The EC of the final equilibrated diluted soil solution and the total amount of water needed to obtain the final equilibrium with the diluted leachant can both be determined. Reeve and Doering (1966a) expressed the concentration of the equilibrated soil solution (EC_{dil}) as $EC_{dil} = EC_{ss}/dn$, where EC_{ss} is the initial high-salt concentration and dn is the dilution factor.

Peterson et al. (1966) determined the amount of water (Diw) required to decrease EC_{ss} to a desired concentration EC_{dil} by the equation:

$$Diw = (D_{dw} EC_{dil} + D_{FC} EC_{FC} - D_{ss} EC_{ss}) / EC_{iw} , \text{ where}$$

D_{dw} is the depth of drainage water (cm),

D_{FC} is the depth of water present at field capacity,

D_{ss} is the depth of soil solution initially present,

EC_{FC} is the electric conductivity of the soil solution at field capacity,

and EC_{iw} is the electric conductivity of the leachant.

In addition to reducing the EC, leaching with suitable water will decrease the ESP. Lowering of the ESP in the root zone of a soil

being reclaimed is the result of a cation exchange between the Ca in the solution and the Na on the exchange complex. The exchange occurs because of a greater activity of Ca compared to Na. This is dependent upon the increased effectiveness according to the "valence-dilution" principle of the Ca present already in the diluted leachant, and would be encouraged also by the increased Ca content from any added Ca amendments. The exchange, which takes place at the interface between the soil and soil solution, occurs in two stages. The first one is rapid and goes to completion within a short period, at ESP values of 5 to 10. The second stage occurs much more slowly and never quite reaches equilibrium. During the first exchange the easily replaceable so-called "active Na" is displaced. Sambur (1963) defined these ions as the "external Na ions of the Na-humate layers" which in turn are adsorbed on to the surface of the clay particles. The so-called "inactive Na", located between the humate layer and the clay surface, is replaced in the second stage and at a slower rate.

After equilibrium of the soil solution with the diluted leachant is obtained, it is also possible to determine the sodium adsorption ratio (SAR_{dil}). Reeve and Doering (1966a) expressed the SAR_{dil} by the equation:

$$SAR_{dil} = SAR_0 / \sqrt{dn} \quad , \text{ where}$$

SAR_0 is the initial SAR, and dn is the dilution factor. The same authors also calculated the amount of water (D_w) needed to decrease the initial ESP of the soil (ESP_0) by a fraction ΔESP , in a given

depth of soil D_s , by the equation:

$$D_w/D_s = (d_s \text{ CEC } \Delta \text{ESP}) / (d_w 100 \Delta (\text{Ca} + \text{Mg}) P) , \text{ where}$$

d_s is the density of the soil,

CEC is the cation exchange capacity,

d_w is the density of water,

$\Delta(\text{Ca} + \text{Mg})$ is the amount of $\text{Ca} + \text{Mg}$ exchanged, and

P is the exchange efficiency factor.

The factor P depends upon the dilution factor dn and the divalent ion fraction indicator R ($(\text{Ca} + \text{Mg}) / \text{Total Cation Concentration}$). With increasing dn and/or decreasing R , the exchange efficiency P increases, but the authors claimed that R should never fall below .3 or hydraulic conductivity will be restricted.

Shah Muhammed et al. (1969) suggested that the efficiency of reclamation can be increased even more by starting subsequent lower dilutions long before equilibrium between the soil solution and the leachant is obtained. Thus, knowing the amounts of water and amendments used for different rates of decrease in EC and ESP, one is able to determine the total needs for reclamation in a manner requiring a minimum expenditure of money.

Clay Swelling and Factors Affecting It

With the high-salt-water-dilution method of reclamation of saline-sodic soils the accurate location of the boundaries of the

so-called "area of stable permeability" is very important. A rough indication of these boundaries had been obtained from the "threshold concentrations"; however, they could be more clearly defined from the additional information from the "jump-off" concentrations, which can be obtained from swelling tests. Therefore swelling of clay is an exceedingly important factor and an understanding of this phenomena is necessary if reclamation is to be successful.

1. Clay swelling

Clay swelling is primarily a property of "clay domains". Emerson (1959) defined a clay domain as a group of clay crystals oriented and remaining sufficiently close together to allow the group, when in an appropriate media, to be considered as a single unit. One or more clay domains, aided by organic matter, form the linkage between mineral particles in the formation of soil micro-aggregates, of the type illustrated by Figure 4.

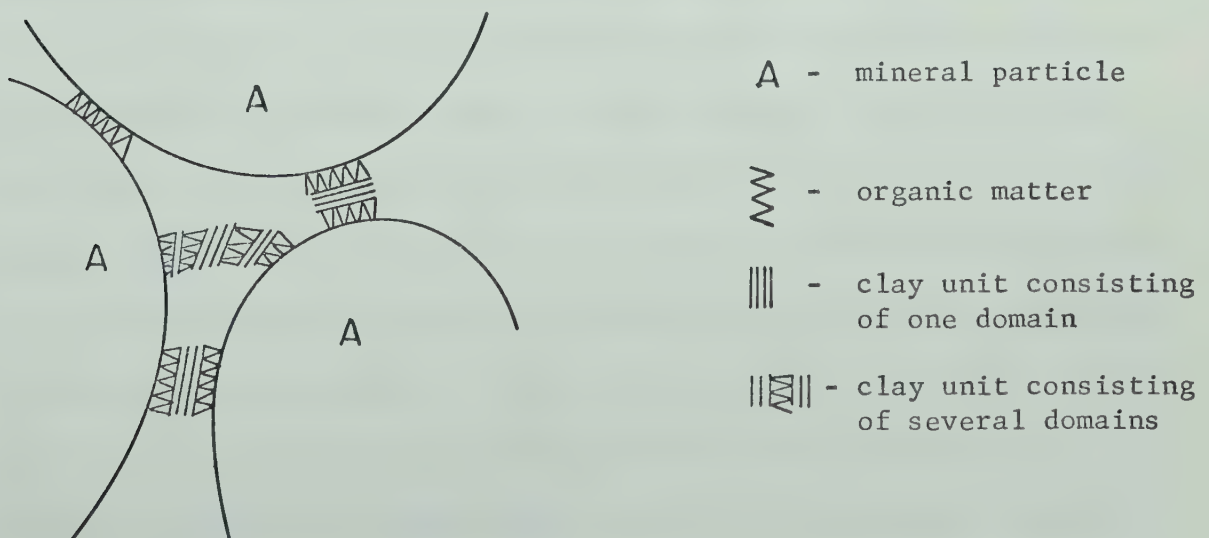


Figure 4. Structure of a micro-aggregate.

The swelling of clay is defined as the change in volume resulting from the adsorption of water on to the crystal surfaces, both exterior and interior. During the process, a non-liquid layer of water is formed on the surfaces of the clay crystal. This water then somewhat resembles a crystalline structure and therefore is termed "quasi-crystalline". In Na-clay systems this quasi-crystalline structure on the inter and intra clay domain surfaces extends with a high degree of order for 75 to 100 Å from the surface of the clay crystal. Beyond that region an attenuated structure may extend an additional 100 to 200 Å. By contrast, water molecules in and around Ca saturated clay domain surfaces show orientation only up to 19 Å (Aylmore and Quirk, 1959). If Ca-clay swelling was only to 19 Å and Na-clay systems were practically unlimited in their swelling capacity, as they are, the swelling behavior of clays would be in accord with the diffuse double layer concept. According to this concept, the amount of swelling depends upon the specific surface area of the clay and the thickness of the diffuse double layer. However, this concept is incorrect for Ca clay systems, because even though the expansion at the internal Ca saturated domain surfaces amounts only to 19 Å, the swelling at the external Ca clay domain surfaces goes far beyond 19 Å. Emerson (1962) contended that Ca clay domains might swell externally, and Na clay domains internally and externally, up to 2,000 to 3,000 Å, in order to form tactoids. In pure Ca saturated clay systems tactoids are built from clay domains which internally have expanded to 19 Å and which externally are linked edge to edge as illustrated by Figure 5.

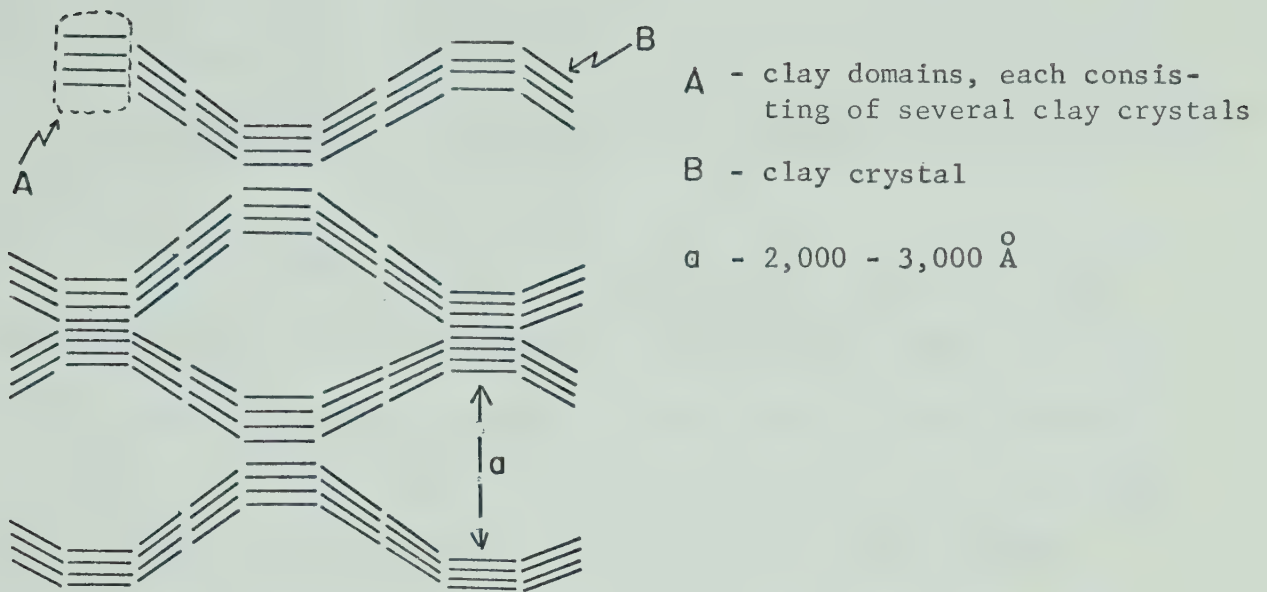


Figure 5. Tactoids in Ca saturated clay systems.

In pure Na systems the tactoids are built from individual clay crystals linked edge to edge, as illustrated by Figure 6.

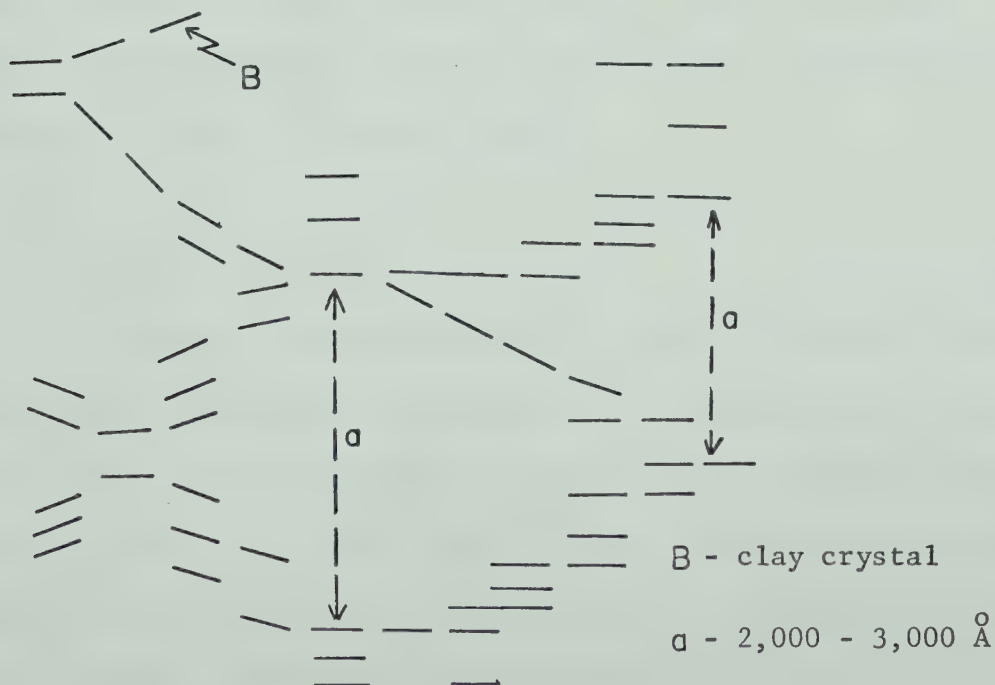


Figure 6. Tactoids in Na saturated clay systems.

In mixed Na and Ca clay soils it is suggested that individual Na saturated clay crystals form the linkages between slightly swollen saturated domains.

Rowell (1969) contended that these inter- and intra-domain swellings, designated by such names as "crystalline", "osmotic", and others, externally proceed in four distinct stages in their process of macroscopic swelling. These are: (a) absence of macroscopic swelling, (b) "jump-off point, (c) lateral swelling that increases linearly, and (d) dispersion and deflocculation. These terms and their characteristics merit discussion.

A. Absence of macroscopic swelling

This first stage, characterized by relatively little macroscopic swelling, corresponds to Norrish's (1954) so-called "crystalline" inter-crystal swelling. During this stage the inter-crystal spacing increases from 9.5 \AA to about 19 \AA .

B. "Jump-off" point

Rowell reported that until stage B is reached the movement of clay particles away from each other is prevented by a net attractive force, the magnitude of which decreases with decreasing electrolyte concentration (Van Olphen, 1963). With a decrease of electrolyte concentration, the forces of attraction and repulsion between adjacent clay crystals reach a point of equilibrium. At this point a reverse of forces takes place (Rowell, 1963). Below the $19 \text{ to } 22 \text{ \AA}$ c-spacing of the lattice, the forces involved are mainly electrostatic and attractive

in character. They include Van Olphen's positive edge to negative face force, hydrogen bonding forces, the attraction between Al and Fe ions and the negatively charged clay surface, and Van der Waal's forces. At larger than 19 to 22 Å c-spacing the dominant forces become repulsive and consist of cation hydration forces, osmotic forces, and London-dispersion forces (caused by overlap of diffuse-double-layers). When expansion exceeds 19 to 22 Å the repulsive forces become dominant, and as a consequence there is an exceedingly rapid expansion from about 19 to 40 Å (Norrish and Quirk, 1954). This phenomena has been termed "jump-off" by Rowell (1969). He termed the related salt concentration the "jump-off" concentration. He proposed that the "jump-off" concentration can be determined by graphical analysis, which is illustrated in Figure 7.

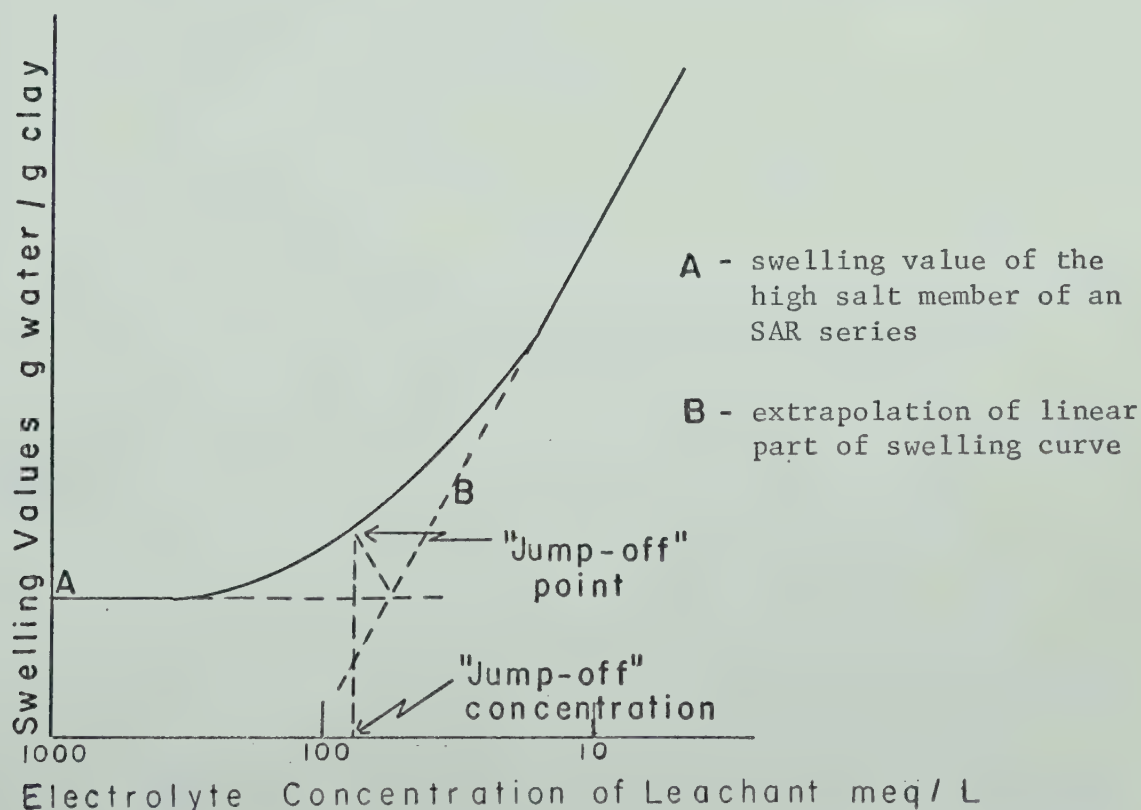


Figure 7. Graphical determination of the "jump-off" concentration.

C. Linearly increased swelling

In Rowell's third stage of macroscopic swelling, the swelling values increase linearly according to the negative logarithm of the concentration (Rowell, 1963), or to the inverse of the square root of the concentration (Norrish, 1954).

Norrish subdivided the third stage of swelling into two distinct regions. The first region has an expansion of the water film from 30 \AA to 130 \AA , and is characterized by what is called "osmotic" swelling. Expansion into the second region, from 130 \AA to $1,300 \text{ \AA}$ is characterized by "edge-to-face-linkages" between clay crystals. Emerson (1963) contended that there are expansions as large as $3,000 \text{ \AA}$ in Na and Ca clays.

Rowell's (1965) concept of the formation of these large pores is presented diagrammatically in Figure 8.

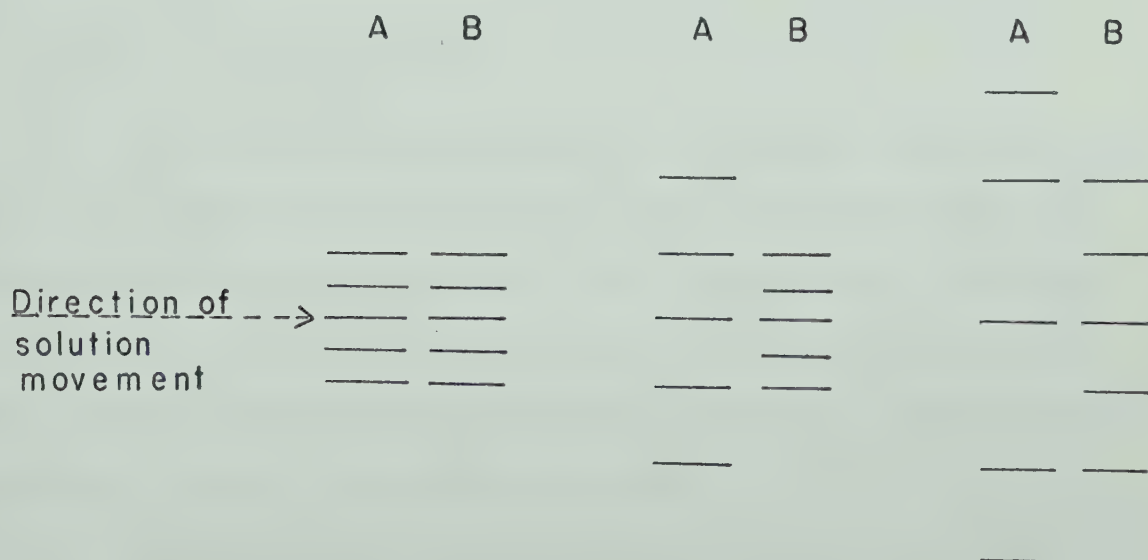


Figure 8. Diagrammatic presentation of the expansion of clay domains.

The first domain immersed in the solution may expand to 40 \AA^0 c-spacings due to "crystalline" swelling. Water then enters the adjacent domain B which starts to expand. Because of the association between crystals of the adjacent domains A and B, expansion of crystals in one domain (B) tends to simultaneously expand the crystals of the associated adjacent domain (A). Sometimes this augmentation of the forces of expansion results in the disruption of the adjacent domain (A).

D. Dispersion and deflocculation

Rowell's fourth stage is the dispersion of clay domains and the deflocculation of clay crystals, of which they are composed. McNeal and Coleman (1966) reported that the subsequent relocation of quartz and clay particles causes the major hydraulic conductivity decrease in coarse textured soils.

2. Factors affecting swelling

Factors affecting swelling of clays need to be considered in relation to the foregoing hypotheses. The major factors affecting swelling are the concentration and composition of ions in the soil solution, the pH, and the per cent of swelling-type minerals in the clay fraction. The effects of these four factors are only noticeable after the "jump-off" point has been reached.

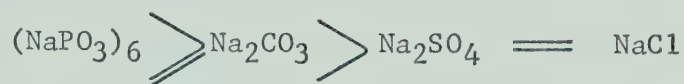
Cations, at low concentrations, are mainly responsible for the initial "crystalline" and the secondary "osmotic" swelling.

But Norrish (1954) contended that at high concentrations the electrolytes decrease the extent of swelling. They accomplish this by replacing the center water molecule of the tetrahedral building units of which the quasi-crystalline structure is constructed. These cations attract all four lone electron pairs of the four remaining water molecules and initiate ion hydration. By doing so, they disrupt the quasi-crystalline structure. As a result, with increases in the electrolyte concentration, the quasi-crystalline structure of the non-liquid layers disintegrates to an increasingly greater extent, consequently diminishing the thickness of the non-liquid layers in particular and swelling in general.

McNeal and Coleman (1966) postulated that clays with both Na and Ca as exchangeable cations consist of discrete homoionic Na domains and discrete Ca domains, of which only the Na domains possess the explosive swelling property. The relative proportion of Ca and Na domains present in a mixed system is closely related to the ESP of the soil (Mungan and Jessen, 1963). The swelling of both monovalent and divalent clay systems is affected by a potential barrier (Aylmore and Quirk, 1960). For monovalent systems swelling after the barrier is passed is controlled by the osmotic property of the diffuse double layer. Divalent cations do not seem to be able to surpass the barrier because of the cation's very strong electrostatic attraction.

Anions indirectly aid swelling because they form dense negative layers around positive bonding sites of the clay surface and around cations. Nakayama (1966) rated four anions according to their

ability to promote swelling:



The charge of aluminum and iron oxides is affected by pH in that they are positive at low pH and negative at high pH (Sumner, 1963). When positively charged, these oxides create additional bonding sites to which negative clay particle faces may adhere. Rowell (1965) contended that clay swelling decreased by one-half when pH decreased from 6 to 2.

Amendments for the Reclamation of Saline-Sodic Soils

Amendments must be considered in a cost and return analysis of reclamation because amendments in general constitute a major portion of the cost of reclamation. The type of amendment to be used will therefore depend upon economic considerations and upon the chemical properties of the soil and the amendment.

During the initial leaching of the high-salt-water-dilution method, it might be practical to use inexpensive Na- and Ca-rich sea water or saline ground water. Reeve and Doering (1966) successfully used Salton sea water containing 600 meq salt per liter and with a SAR of 8. Milne and Rapp (1966) used saline ground water with a salt content of 50 meq salt per liter and a SAR of 35. They encountered no difficulties. For the subsequent diluted leachings during which exchange of Ca and Na takes place, Ca-rich amendments have to be added to the diluted leaching water in most cases. From the purely economic

point of view, CaSO_4 is the most practical Ca compound to use. However, Graveland (1960) reported that gypsum should not be used for western Canadian soils with ESP values over 25 because, due to its low solubility, CaSO_4 does not provide Ca in sufficiently large quantities to maintain permeability.

Effect of Salinity on Plant Growth

In highly saline soils the high osmotic pressure and the toxic amounts of ions are the major inhibiting factors to plant growth (Hayward and Wadleigh, 1949). Furthermore, high ESP's (>40 per cent) decrease the availability of calcium, while on the other hand low ESP's (<5 per cent) tend to have a stimulating effect upon plant growth (Pearson and Bernstein, 1958). Along with the chemical inhibiting factors are physical factors, such as water logging and crusting, which oppose plant growth too.

In slightly saline soils the unbalanced ionic environment rather than the salt itself adversely affects plants (Heimann, 1959). Consequently, in such soils fertilizers may be applied to improve the balance.

Summary of Literature Review

On the basis of the foregoing review, the steps in reclamation of a saline-sodic soil by the high-salt-water-dilution procedure

may be summarized as follows:

- (1) Establishment of good drainage.
- (2) Determination of the "threshold" and "jump-off" concentrations of the soils concerned.
- (3) Initial leaching with high-salt-water and subsequent leachings with appropriately chosen dilutions of the high-salt-water.

The amount of dilution must lie well within the limits set in

(2) above and must be based on cost-benefit analysis.

MATERIALS AND METHODS

Surficial Geology and Soils

The Maple Creek "V" projects are located in one of the most arid regions of the Canadian Prairies. Southwestern Saskatchewan forms a large plain that initially was overlain by unconsolidated glacial till. However, glacial meltwater and winds caused sorting of the materials; as a result the surface of the prairie plain is highly diversified. Ridges of glacial till alternate with sand dunes and glacial lake clay flats. The "V" projects are of the latter type. The surrounding sandhills converge from the southeast and west to form a "V" and this was the origin of the name, Maple Creek "V" projects.

The projects are located at the confluence of the Bigstick Basin and a long flat extending from Bitter Lake eastward to Bigstick Lake. This long narrow flat overlies the basement of a preglacial channel that commences at Medicine Hat, 128 km to the southwest. According to Milne and Rapp (1966) the channel contains seams of coarse sand and gravel 18.5 meters in thickness. These form an excellent aquifer with a capacity of approximately 216 million cubic meters of water. This aquifer is overlain by a lacustrine clay deposit which is 12 meters thick in the center of the project and thins out near the margins where it eventually is replaced by sand dunes.

The soils of the Maple Creek "V" projects are designated as saline Regosols in the Canadian soil classification system. They were developed on a fine textured lacustrine material.

Sources and Quality of Water

The major supply of water for the "V" projects came from Junction Reservoir (see Fig. 1). This water was of excellent quality, as its rating C_2S_1 indicated (Table 1). However, the low and variable spring runoff was insufficient to fill the upstream reservoirs. Also, seepage and evaporation losses from the reservoir and its drainage channels were very high. As a result a recurrent water deficiency from this source had to be expected.

In view of the foregoing, extensive use was made of a second major supply of water, the aquifer underlying the irrigated area and extending south beneath Tennaille Lake. The aquifer held approximately 216 million cubic meters of water (Milne and Rapp, 1966). However, the quality of this water decreased with progression from the Upper "V" to the Lower "V", as the respective ratings C_3S_1 and C_4S_2 indicated (Table 1).

Laboratory Analyses

Laboratory analyses were performed on both field and laboratory prepared soil samples. A representative sample for each laboratory soil core was taken while field samples were taken from each foot of soil profiles selected at regular intervals in the plot areas. The soil samples were oven dried at 60°C and ground to pass a 2 mm sieve. The processed samples were then subjected to a number of common determinations.

Table 1. Chemical analysis of irrigation water

pH	EC mmhos/cm	Soluble salts, meq/L					SAR	Residual Na ₂ CO ₃ meq/L	Water class*
		Na	Ca + Mg	SO ₄	CO ₃	HCO ₃			
Junction Reservoir									
7.3	1.1	5.5	6.2	7.2	--	3.6	3.1	0.0	C ₂ S ₁
Upper "V", pump well No. 2 (see Fig. 2)									
7.8	2.3	17.5	12.1	12.7	--	13.8	7.1	0.9	C ₃ S ₁
Lower "V", pump well No. 5 (see Fig. 3)									
7.7	5.0	40.5	22.0	38.1	--	17.6	12.1	0.0	C ₄ S ₂

* Symbols for water class as per U.S.D.A. Handbook 60.

1. Physical analyses

(a) Mechanical analyses. Mechanical analyses were done according to the pipette method described by Toogood and Peters (1953).

(b) Disturbed hydraulic conductivity. Disturbed hydraulic conductivity values were determined according to the method described by the U.S. Salinity Laboratory Staff (1954). The soil column (ΔL) in the plastic permeameters was 8.5 cm deep, and above that a constant 8 cm column of water was maintained. The hydraulic head difference (ΔH) was assumed to be the length of the soil and water column together (16.5 cm). Percolation rates were read twice, after intervals of one-half hour.

(c) Saturation percentages. Saturation percentages were determined from the volume of water added, according to the method described by the U.S. Salinity Laboratory Staff (1954).

2. Chemical analyses

(a) pH. pH of the soil paste was determined with a Fisher Acumet Model 19, pH meter equipped with a glass electrode and a calomel electrode. The pH of the leachates was measured with a Beckman Zero-matic pH meter fitted with a glass and a calomel electrode.

(b) Electrical conductivity. EC measurements of the soil saturation extracts were done with a Yellow Springs Instr. Co. Conductivity Bridge, No. 31. Determinations on the leachates were

made with an Industrial Instr. Inc. Conductivity Bridge, No. R.C. 1201. Results were expressed as mmhos/cm.

(c) Soluble salts. The soluble sodium and the soluble calcium plus magnesium in the saturation extracts and leachates were determined with a Technicon Auto Analyzer, Model I, employing the method described by Chang and Van Schaik (1966). The Technicon Auto Analyzer consists of a Beckman direct-reading flame photometer for the sodium content determination and a colorimeter to measure calcium plus magnesium. Before the colorimetric measurement the solution is treated with Na_2Mg EDTA and calmagite indicator.

The chloride content of the saturation extracts and leachates was determined on a Beckman Expanded scale pH meter, Model 76, fitted with a chloride ion silver chloride electrode and a calomel reference electrode. The solution was buffered with potassium hydrogen phthalate and was subsequently titrated with 0.25N AgNO_3 until the potential read 0.8 millivolt.

The carbonate and bicarbonate contents were measured with a Beckman Expanded Scale pH meter, model 76, equipped with a glass indicator electrode and a calomel reference electrode. In order to determine the carbonate content the solution was titrated with 0.02N H_2SO_4 until a pH of 8.0 was reached. For bicarbonates the solution was titrated with 0.02N H_2SO_4 to a pH of 4.4.

The soluble sulphates were determined by the difference between the soluble cations expressed as milli-equivalents and the soluble anions of chloride, carbonates, and bicarbonates.

(d) Exchangeable cations and exchange capacity. Exchangeable cation measurements were made on extracts obtained as described by the U.S. Salinity Laboratory Staff (1954), the reading being made employing a Beckman direct-reading flame photometer.

The cation exchange capacity was determined by difference between the total sodium content and the soluble sodium content. The total sodium content of the soil was determined by extracting the sodium saturated soil with 1N NH_4OAc and measuring the sodium content of the extract with a Beckman flame photometer, Model 4100.

(e) Gypsum content and requirement. The gypsum content and requirement determinations are described by the U.S. Salinity Laboratory Staff (1954). In the gypsum content determination the gypsum was initially purified with acetone.

(f) Sodium adsorption ratio. SAR, was determined as follows:

$$\frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{++} + \text{Mg}^{++}}{2}}}$$

where Na^+ = meq/L of sodium,

Ca^{++} = meq/L of calcium,

Mg^{++} = meq/L of magnesium, in the soil solution.

(g) Exchangeable sodium percentage. ESP, was calculated as follows:

$$\frac{\text{Na}^+}{\text{CEC}} \times 100\% \quad \text{where } \text{Na}^+ = \text{meq Na on the}$$

exchange complex and CEC is cation exchange capacity.

3. Mineralogical analyses

(a) Segregation of the total clay fraction. Clay separation was done according to the method described by Brydon (1957). The organic matter was oxidized with 30 per cent H_2O_2 and was removed along with the soluble salts by means of centrifuging and decantation. The samples were then dispersed by alkalizing with 0.1N NaOH. Subsequently the samples were placed in volumetric beakers from which the top 8 cm containing the clay suspension was decanted after standing for 6 hours and 8 minutes.

(b) X-ray analyses of clay minerals. The clay suspensions were mounted on glass slides which were glycolated in a saturated atmosphere of ethylene glycol. Duplicate slides were heat treated to $550^{\circ}C$ and stored in a desiccator. A Philips X-ray diffractometer with a high angle goniometer was used for identification of the clay minerals present. The X-ray generator was operated at 40 kw and 20 ma using CuK radiation with a nickel filter. Scanning speed was one degree 2θ per minute and chart speed one cm per minute.

4. Assessment of past and present reclamation in the field

Reclamation of the salt affected Maple Creek "V" projects was studied for three separate objectives. The first one was to compare the uniformity and rate of reclamation of borderdike and basin types of irrigation. The second objective was to compare reclamation under various groundwater conditions, and the third reason was to obtain rates of field reclamation which would be used later for

comparison with results obtained from simulated reclamation schemes in the laboratory.

In order to compare reclamation between conditions as variable as stated above, chemical and physical data were collected from three distinctly different areas. These three areas were: the Upper "V", lot 9 (see Fig. 2), which had a borderdike type of irrigation and was inside the range of influence of drainage pump No. 2; the Upper "V", lot 16, which also had a borderdike type of irrigation, but which was outside the influence of any drainage pump; and the Lower "V", basins (see Fig. 3), which had a basin type of irrigation.

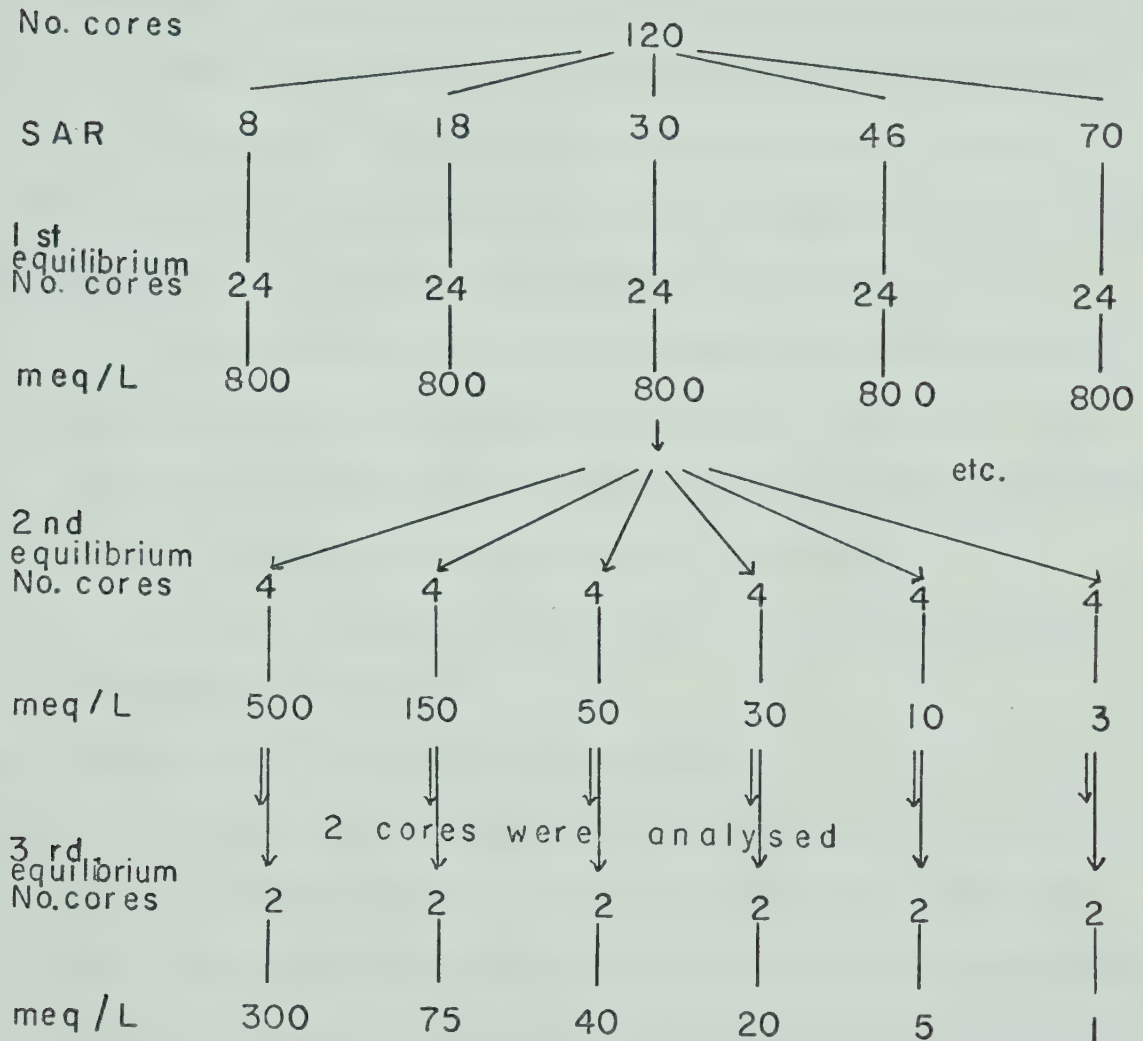
The area was sampled twice a year, once in the spring and once in the fall. Soil samples were taken with a Sterling drill from the first 15 cm, the second 15 cm, and from each subsequent 30 cm to a depth of 180 cm. On the borderstrips the sampling sites were located in the center of each strip at 76 and 226 meters from the supply ditch on lot 9, and at 76 and 260 meters from the supply ditch on lot 16. On the basins 3 sites per basin were randomly selected at approximately 75 meters from the centrally located drain ditch.

5. Hydraulic conductivity tests

Hydraulic conductivity tests were conducted for the tentative determination of the "area of stable permeability" (Quirk and Schofield, 1955). This "area" indicated the EC and SAR values of the leachants for which the HC of the soil would remain high and as such bring the rate of reclamation to a near maximum.

A wide variety of solutions was needed varying both in terms of concentration of salts, i.e. meq/L, and also in terms of composition, i.e. SAR values. One hundred and twenty plexiglass cylinders, 21 cm in length and 6.3 or 7.8 cm in diameter were used as permeameters. Soil samples were carefully poured in the permeameters and compacted by dropping the permeameter 10 times through a distance of 2.5 cm. Appropriate amounts of soil were used to give 14.5 cm long soil columns. The columns were then leached with 800 meq/L salt solutions (mixtures of NaCl and CaCl₂) with SAR values of 8, 18, 30, 46, and 70. This then would eliminate the effects of SAR and the obstruction by air bubbles and dispersed soil particles. Consequently, subsequent decreases in HC would be solely the result of reductions in EC of the leachant. A constant hydraulic head of 2.6 cm was maintained. This treatment continued until equilibrium was reached with respect to HC, EC, and SAR after one month. Then each of the five SAR series was split into 6 groups of 4 soil columns each. The 6 groups were exposed to 6 different salt concentrations of the same SAR value as in previous leaching: 500, 150, 50, 30, 10, and 3 meq/L. Again a score was kept on the HC, EC, and SAR to see when the soil solution reached equilibrium, which finally occurred after 1.5 months. After this second equilibration, two out of each set of four cores were removed for laboratory analyses. The remaining two cores were now treated with leachants of lower concentrations: 300, 75, 40, 20, 5, and 1 meq/L. Leaching continued again until equilibration was attained, after which the soils were sampled, analyzed, and used

for the greenhouse study. The procedure is illustrated in the following flow chart.



Note -- Throughout this thesis the 800 meq/L solution will be referred to as the high salt solution. Solutions of 500, 300, etc. meq/L as a series for each SAR used, thus we shall speak of the SAR 8 series, the SAR 18 series, etc.

6. Swelling tests

The swelling tests were designed to determine the "jump-off" concentrations which would hopefully confirm the tentative delineation

of the "area of stable permeability" found in the previous section. The swelling tests were carried out on the 2 μ clay fraction of the soil. The clay fraction was extracted with a minimum of alteration in order to retain the organic matter, the iron and aluminum oxides, as well as the clay. The procedure was similar to that by Rowell (1969) except for some minor modifications. The method was as follows:

(a) Preparation of a homo-ionic N NaCl clay suspension.

(1) Total clay fraction was separated from 750 g of soil, according to methods used by the Alberta Soil Survey and Department of Soil Science staff. Beforehand, the soil had been exposed twice to eight pore volumes of 2N NaCl solution.

(2) Next, NaCl was added to the clay suspension until its concentration reached 1N.

(b) Preparation of oriented clay aggregates.

A 1.5 ml sample of clay suspension was pipetted on to each 1.6 x 1.6 cm microscopic cover slide, previously covered with a thin film of Dow Corning Stopcock grease, to improve the adherence of the clay aggregates onto the slide. The clay aggregates were then dried for 48 hours over P_2O_5 .

(c) Determination of swelling values.

(1) Pairs of slides were placed in solutions as prepared for the permeability tests, described earlier, with SAR values of 8, 18, 30, 46, and 70, concentrations of 3, 10, 30, 50, 150, 500, and 800 meq/L each, and at two different pH values of 7.5 and 4, for a total of 70 treatments and 140 slides.

(2) After being submerged for 48 hours, the aggregates on the slides were carefully surface-dried with filter paper and weighed.

(3) Subsequently the aggregates were dried for 48 hours over P_2O_5 and weighed again.

The difference between the two weighings indicated the amount of water absorbed. From the amounts of clay used and the amounts of solution absorbed, the swelling values (grams of absorbed water per gram of clay) could be calculated.

The subsequent determination of the "jump-off" concentration occurred in a slightly modified manner from that of Rowell (1969). He defined the "jump-off" concentration as the concentration related to the point of intersection between the horizontal line extending from the swelling value of the basic high salt solution (.8N) and the extension of the linear logarithmic curve of the swelling values at low concentrations. However, this definition disregarded the gradual increase of the swelling values between the 300 and 30 meq/L concentrations. Therefore, the projection of Rowell's intersection point upon the swelling curve rather than the intersection point itself should be considered as the "jump-off" point.

Greenhouse Study

Greenhouse studies permitted the determination of relative yielding ability at the various salinity levels. For this study one quart plastic pots were used. Pots were prepared as follows: 100 g of

medium textured sand was placed at the bottom of each pot; a 1:3 mixture by volume of vermiculite with 800 g of soil was subsequently placed on top of the sand. Two pots were prepared as checks with original soil. The other 30 pots were prepared with the leached soil that was treated during the permeability tests.

In each pot 10 Galt barley seeds and 6 Vernal alfalfa seeds were placed. Pots were watered daily and fertilizer was supplied as three separate applications equivalent to a total of 125 kg of N, 75 kg of P_2O_5 , and 65 kg of K_2O per hectare. After germination the seedlings were thinned to 5 barley plants and 4 alfalfa plants. When the barley was 2 months old, it was harvested, oven dried, weighed and analyzed for per cent N and per cent P. In a similar way, after 4 months the alfalfa was cut, oven dried, and weighed.

To determine the revenues from extra crop yields resulting from the artificial reclamation, three steps had to be taken. First, the amounts of growth per pot had to be converted to more meaningful comparable field yields. For this purpose the highest yield of barley dry matter per pot in the laboratory was assumed to be equivalent to a 3,038 kg per hectare yield of grain in the field. Secondly, the various levels of desalinization of the soil, which resulted from natural reclamation during the years following the initial artificial reclamation, had to be estimated. Natural reclamation would result from the applications of irrigation water and the action of crop residues. To approximate the salinity levels during the natural reclamation, soil of the Maple Creek "V" projects was leached in the laboratory with solutions similar to well No. 2 water. The EC and SAR values of these

leachates were subsequently assumed to be equivalent to the EC and SAR of the soil solution of the soil in a field leached under similar optimum reclamation conditions. Thirdly, the crop yields related to these salinity levels had to be estimated and added for each salinity level. The difference between the total yields of the initial unreclaimed and a partially reclaimed soil gave the extra crop yields. Multiplied by the price of barley, it gave the extra crop revenues.

Costs of Reclamation

The costs of artificial reclamation to the various desalinization levels were the combined charges for water, amendment, and labour. For determining the maximum profit as a result of artificial reclamation, the minimal cost of reclamation for each salinity level should be determined. For this, the various routes of desalinization were plotted from EC and SAR data of the leachates from the various HC tests.

To further minimize the cost the cheapest source of water and amendment was selected. Creek water, which was the cheapest with respect to pumping, was used as much as possible for the less saline solutions. For the more saline solutions, the salts already present in the well No. 2 water, and the fact that pumping from the well was necessary to lower the aquifer, made it more economical to use well No. 2 water. To determine the most efficient amendment, a leaching test was set up in which three sets of cores with three different salts: $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$, and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, each containing 10 T Ca / 30 cm ha, were leached with tap water.

RESULTS AND DISCUSSION

Physical and Chemical Properties of the Soil

In the Upper "V", the soils were uniformly fine textured while the Lower "V" had coarser textured alluvial material inter-layered with the finer lacustrine material (Table 2). The subsoils of both projects consisted of variable intermingled strata of water deposited sands, silts, and heavy clays. The hydraulic conductivities of the soils of these projects were very low (<0.1 cm per hour) because of the large percentage of clay, which was mainly montmorillonite. As a result the soils were poorly drained and very difficult to manage.

The chemical data (Table 2) indicated that the surface soils of the "V" projects are relatively high in soluble salts. EC values ranged from 2.4 to 21.2 mmhos/cm, SAR values from 9.6 to 42.2, and pH values from 7.9 to 8.7, and in all three cases they increased with depth. Gypsum contents varied from 0 at the surface to 50.3 T/30 cm hectare at greater depths in the profile. The salts were predominantly (60 per cent) sulphates of Na, Mg, and Ca. The remaining 40 per cent of the salts were primarily chlorides and bicarbonates. In places, where salts tended to accumulate on the soil surface, Na salts were dominant and Mg salts were next in importance. The soils in general lacked carbonates and were low in fertility. Saturation percentages and CEC values were high, as expected in soils with high percentages of clay and silt.

Table 2. Analyses of two typical profiles and the soil used for laboratory experiments

Depth cm	Mechanical analysis						% Satur- ation	pH	EC mmhos/cm	Soluble salts, meq/L					CEC meq/100 g	ESP	CaSO ₄		HC cm/hr		
	Texture	% S	% Si	% C		Na				Ca + Mg	Cl	HCO ₃	CO ₃	SO ₄			SAR	Content T/30 cm ha		Requirement T/30 cm/ha	
				Coarse	Fine																
Typical profile from Upper "V": Lot 16 (see Fig. 2)																					
0-15	SiC	8	45	18	29		83	8.1	2.4	22	11	6	7	--	20	9.6	37	14.2	0.0	4.3	0.0
15-31	SiC	2	43	24	31		128	8.2	4.4	35	12	6	5	--	35	14.3	48	19.0	0.5	1.2	0.0
31-61	SiC	3	49	18	30		118	8.2	10.6	95	52	12	3	--	132	18.7	44	24.4	2.6	3.4	0.1
61-92	SiC	4	46	36	14		110	8.3	13.4	123	58	15	3	--	163	22.8	42	30.7	15.4	0.0	0.1
122-153	SiC	3	41	25	31		138	7.9	12.5	123	61	15	2	--	167	22.2	45	28.5	9.3	0.0	0.0
Typical profile from Lower "V": Basin 4 (see Fig. 3)																					
0-15	C	2	30	33	35		128	8.0	2.5	18	8	2	6	--	17	9.7	56	11.5	0.0	5.7	0.0
15-31	C	2	25	33	40		124	8.0	5.6	39	26	5	4	--	56	10.8	58	15.8	0.0	3.1	0.0
31-61	C	1	32	30	37		160	8.1	8.5	67	52	9	2	--	108	13.2	51	14.2	1.7	0.3	0.0
61-92	SiCL + FS	43	30	9	18		70	8.2	11.2	94	61	18	2	--	134	17.0	25	26.5	18.6	2.9	0.1
122-153	C	6	39	23	32		152	8.2	11.2	100	68	12	2	--	154	17.2	45	19.4	12.7	0.0	0.0
Soil used for laboratory experiments																					
31-92	SiC	6	43	23	28		113	8.7	21.2	299	106	31	4	--	369	42.2	42	50.3	20.3	0.0	0.0

Mineralogical data indicated that interstratified layers of montmorillonite and illite were dominant. Next in abundance was discrete montmorillonite with some minor illite and quartz, while only traces of kaolinite were present. An example of the diffractometer patterns of the oriented aggregates is shown in Figure 9. The 15.24 Å c-spacing in the air dry treatment and the 17.33 Å spacing in the glycolated state, both indicate the randomly interstratified montmorillonite and illite as outlined by Kodama and Brydon (1964). The composition of the clay fraction resembles to some extent that of the underlying Upper Cretaceous Bearpaw formation, which is high in montmorillonite and illite (Byrne and Forvolden, as quoted by Kodama and Brydon, 1964).

Assessment of Past and Present Reclamation in the Field

In order to determine and compare the uniformities and the rates of reclamation on the border dike and basin systems, chemical and physical data had been collected earlier from the test area (Milne and Rapp, 1966). In this study further sampling was done and more analytical data attained. Two assumptions were made regarding these data. First, the four parameters: EC, SAR, pH, and HC, were considered to indicate quite accurately the state of reclamation. The second assumption was that the data obtained from sampling during the fall would be reliable indicators of that state of reclamation. The reason for introducing the last assumption was the great variability between chemical data obtained from spring and fall sampling. Table 3 indicates a slight increase in the EC of lot 9, and a large increase in the EC's of lot 16 and the basins during the summer of 1969. Van Schaik and

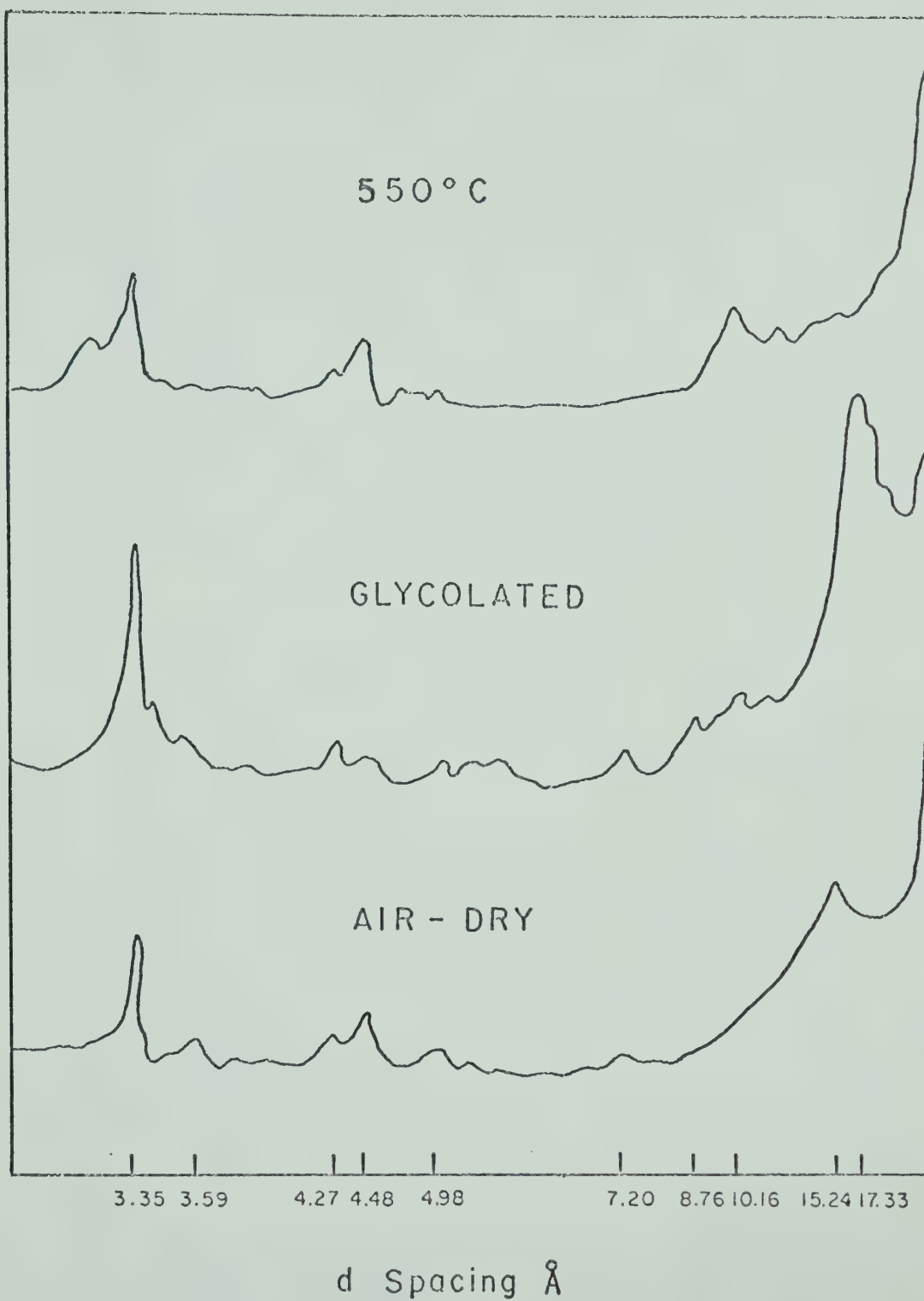


Figure 9. X-ray diffraction patterns of oriented specimens of the total clay fraction after various treatments.

Table 3. EC and SAR values of the study areas

Location	Distance from supply ditch meters	EC (Average for profile)							SAR					Change %/yr	
		1962 Oct.	1963 Oct.	1965 Aug.	1967 Oct.	1969 May	1969 Oct.	Change %/yr	1962 Oct.	1963 Oct.	1965 Aug.	1967 Oct.	1969 May		1969 Oct.
Upper "V", Lot 9	76	12.5	8.5		8.5	6.0	6.7	-6.9	27.0	19.3		18.7	22.5	19.5	-3.7
	228	21.0	17.5		18.0	13.5	15.0	-4.7	29.0	26.0		27.5	30.0	27.8	-0.5
	Mean	16.3	13.0		13.3	9.8	10.9	-5.8	28.0	22.7		23.1	26.3	23.7	-2.1
	Deviation from the mean	4.7	4.5		4.7	3.8	4.1	1.1	1.0	3.3		4.4	3.7	4.1	1.6
Upper "V", Lot 16	76			21.8	20.0	17.0	18.5	-4.5			32.8	35.0	30.9	29.7	-2.3
	260			19.5	16.3	19.5	17.0	-5.7			29.5	23.5	23.0	24.5	-4.1
	Mean			20.7	18.2	14.8	17.8	-5.1			31.2	29.3	27.0	27.1	-3.2
	Deviation from the mean			1.2	1.8	2.3	0.8	0.6			1.7	5.7	4.0	2.6	0.9
Lower "V", Basins	Upstream Basins				15.5	11.8	16.0	+1.5				22.1	20.1	22.5	+1.4
	Downstream Basins				10.3	13.0	12.0	+8.3				17.3	17.5	15.5	-5.0
	Mean				12.9	12.4	14.0	+4.9				19.7	18.8	19.0	-3.2
	Deviation from the mean				2.6	0.6	2.0	3.4				2.4	1.3	3.5	1.8

Milne (1963) and Graveland (1960) contended that under a plant cover the salt content of the soil solution increased during the summer in proportion to the amount of water taken up by the plants. Furthermore these workers noted also increases in SAR and pH during the summer months. Similar results were obtained for lot 16 during the summer of 1969. In contrast, the SAR and pH of lot 9 and the basins dropped (Tables 3 to 6), possibly because of larger applications of irrigation water on lot 9 and a high content of gypsum in the basins. However, to avoid the seasonal changes in the salt content and composition of the soil solution, only the data obtained from fall samplings were used for the determination of the rate and uniformity of reclamation.

Data for lot 9 are presented in Figure 10 and Tables 3 and 4. Figure 10 shows graphically the EC and SAR values in 1962, 1967, and 1969 of typical profiles in the upslope and downslope regions of the borderstrips. At 76 meters from the supply ditch, i.e., the upslope region, EC, SAR, pH and HC were all substantially less (EC 6.7 - 12.5 mmhos/cm, SAR 18.7 - 27.0, pH 8.01 - 8.31, HC .004 - .036 cm/hr) as compared to values at 228 meters from the supply ditch, i.e., the downslope region (EC 15.0 - 21.0 mmhos/cm, SAR 26.0 - 29.0, pH 8.14 - 8.39, and HC .026 - .037 cm/hr). In addition the rates of desalinization taken with respect to the values of 1967 were greater at 76 meters (EC -6.9%/yr, SAR -3.7%/yr, HC 0.0 %/yr, pH -1.3 %/yr) as compared to those at 228 meters (EC -4.7 %/yr, SAR -0.5%/yr, HC +20.8 %/yr, pH -2.7 %/yr) (Tables 3 and 4).

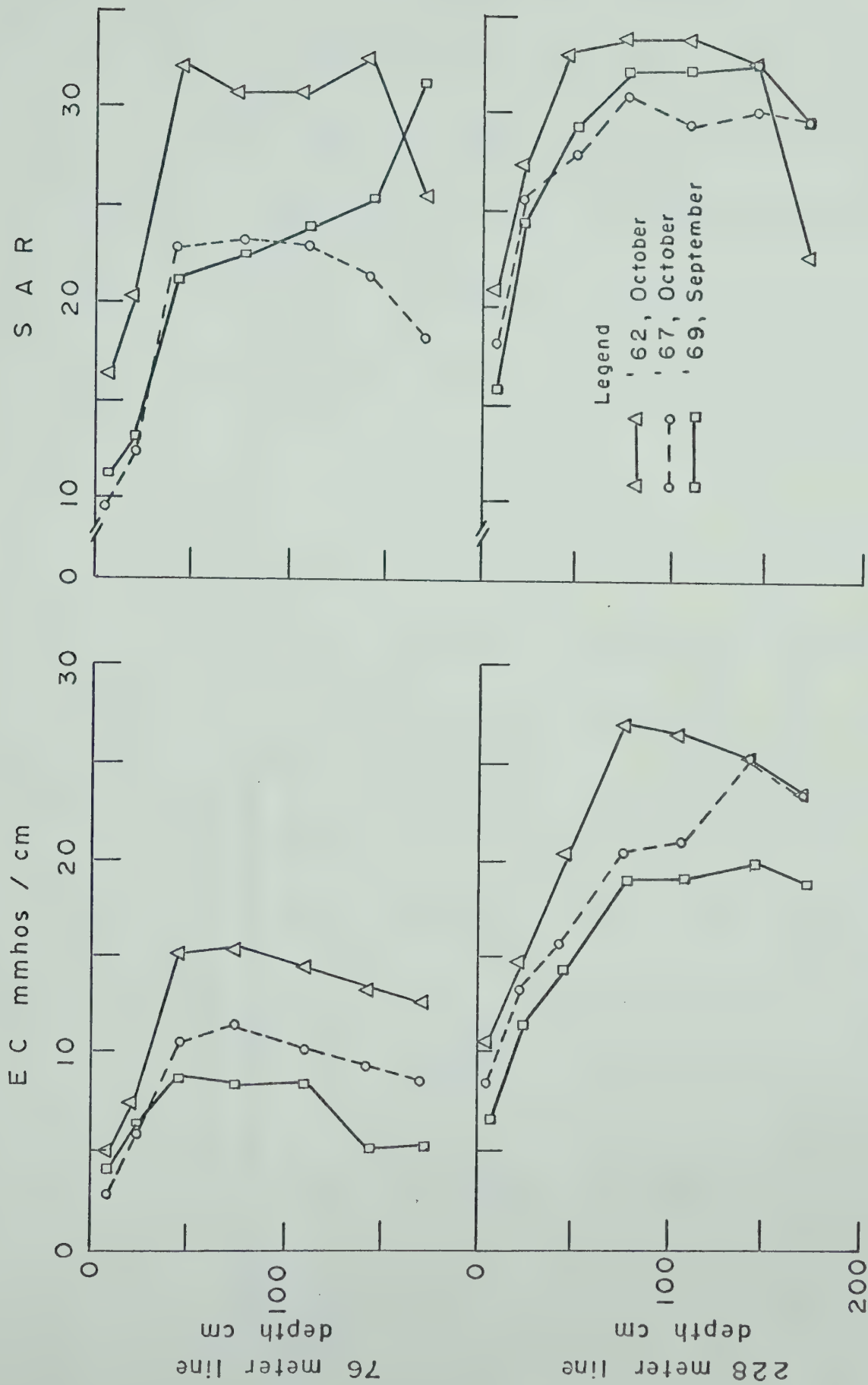


Figure 10. EC and SAR values of profiles at 76 and 228 meters from the supply ditch, on lot 9, Upper "V".

Table 4. pH and hydraulic conductivity values of Lot 9, Upper "Y"

Distance from supply ditch meters	Depth cm	Texture	pH					HC, cm/hr					Change %/yr
			1962	1963	1967	1969	Change	1962	1963	1967	1969	Change	
			Oct.	Oct.	Oct.	May	%/yr	Oct.	Oct.	Oct.	May	%/yr	
76	0-15	CL	8.2	8.3	7.9	8.1	7.8	--	--	--	.03	.03	
	15-31	CL	8.1	7.9	8.0	8.1	7.9	.03	--	.07	--	--	
	31-61	SiCL-C	8.4	8.0	8.0	8.3	8.3	--	--	.12	.07	--	
	61-92	SiCL-C	8.4	8.0	8.0	8.5	8.2	.03	--	.03	--	.03	
	92-122	SiCL-SC	8.4	8.0	8.2	8.6	8.3	.03	.03	--	--	.03	
	122-153	SiCL-SiC	8.4	8.1	8.3	8.5	8.5	--	--	--	--	--	
	153-183	SiCL-SiC	8.3	8.1	8.1	8.4	8.4	--	--	.03	.03	--	
Average			8.31	8.06	8.07	8.36	-1.3	.013	.004	.036	.019	.013	0.0
228	0-15	CL	8.2	8.2	8.1	8.3	8.0	--	--	--	--	--	
	15-31	CL-C	8.3	8.1	8.1	8.2	8.1	--	--	.07	.05	.03	
	31-61	SiCL-C	8.3	8.2	8.1	8.2	8.2	--	--	.03	.10	.03	
	61-92	SiCL + S	8.5	8.3	8.1	8.4	8.1	.07	.05	.03	.05	.03	
	92-122	SiCL + SC	8.6	8.3	8.1	8.3	8.2	--	.05	.03	.05	.03	
	122-153	SiC	8.4	8.4	8.2	8.4	8.3	.03	.03	.03	.05	.05	
	153-183	SiC + FSL	8.4	8.3	8.3	8.4	8.2	.07	.05	.07	.05	.03	
Average			8.39	8.26	8.14	8.31	-2.7	.024	.026	.037	.050	.029	+20.8
Mean			8.35	8.16	8.11	8.33	-2.0	.019	.015	.036	.035	.021	+10.4
Deviation from the mean			.04	.01	.04	.02	.7	.006	.011	.0	.015	.008	10.4

What was the reason for the lower salinity and the greater rate of desalinization in the upslope region? The main cause was the use of larger quantities and better quality water in the upslope region. However, the decrease in SAR was also a result of the greater ease with which monovalent cations moved through the soil as compared to divalent cations (Muratova, 1958). The lower HC was mainly caused by the heavier texture but possibly also the lower EC could have induced deflocculation of the colloidal soil materials and consequently caused additional HC decreases.

For lot 16, the chemical and physical data are presented in Figure 11 and Tables 3 and 5. The results tended to be the opposite to those of lot 9. In lot 16, the EC, SAR, and HC were higher at 76 meters (EC 18.5 - 21.8 mmhos/cm, SAR 29.7 - 32.8, and HC .164 - .294 cm/hr) than at 260 meters from the supply ditch (EC 16.3 - 19.5 mmhos/cm, SAR 23.5 - 29.5, and HC .011 - .023 cm/hr) while the pH was similar for both regions (pH 8.14 - 8.26). Also, in contrast with lot 9, the rate of desalinization at lot 16 was the least at 76 meters from the supply ditch (EC -4.5 %/yr, SAR -2.3 %/yr, HC +69.0 %/yr, pH +0.9 %/yr) while the rate of change was the greatest at 260 meters (EC -5.7 %/yr, SAR -4.1 %/yr, HC +4.4 %/yr, pH +1.5 %/yr).

The major cause of the higher salinity on the upslope end was the discharge of seepage water from the unlined supply ditch which to some extent defeated the effect of the larger applications of irrigation water on this end. The higher HC in the upslope region was caused by a lighter texture there.

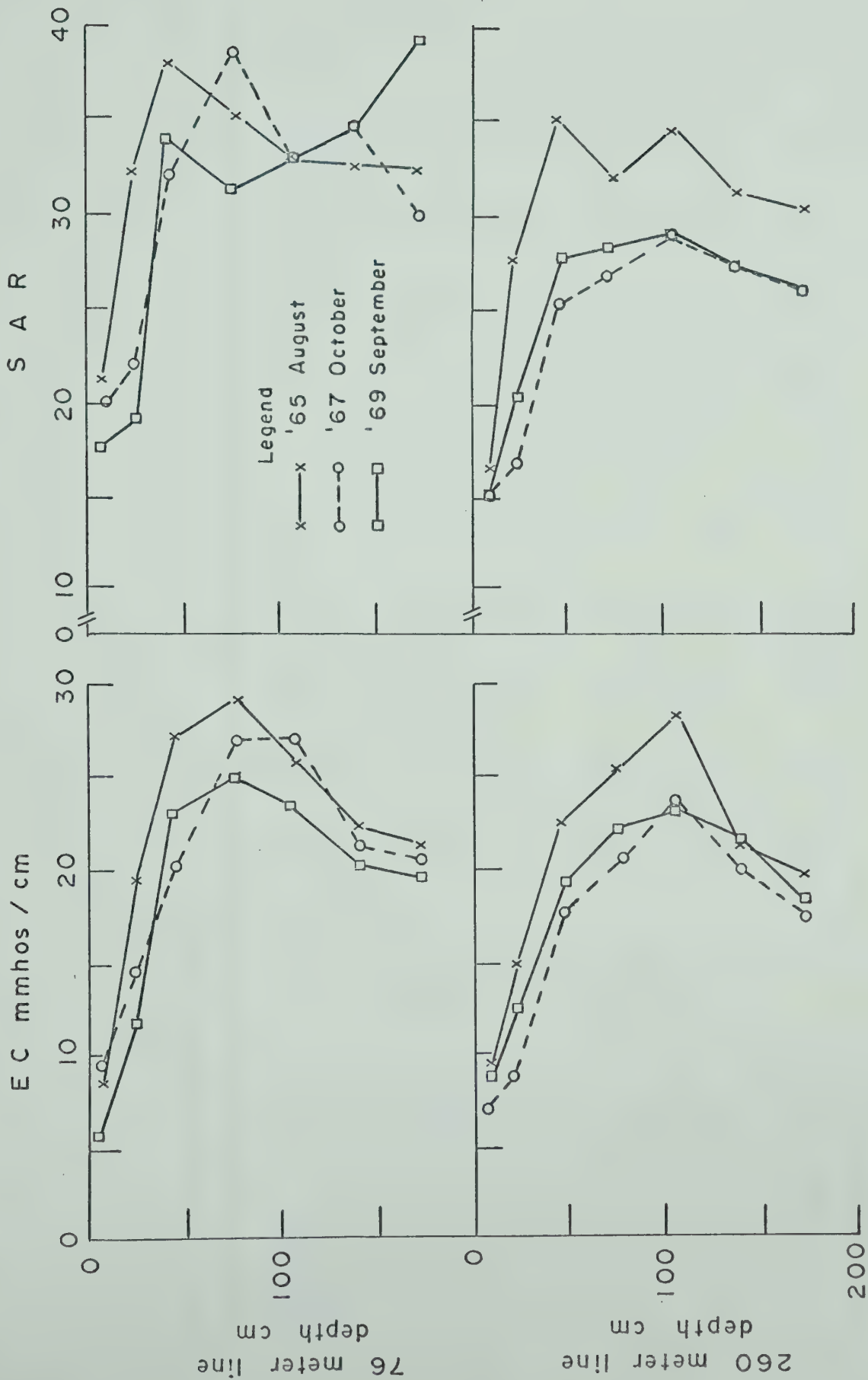


Figure 11. EC and SAR values of profiles at 76 and 260 meters from the supply ditch, on lot 16, Upper "V".

Table 5. pH and hydraulic conductivity values of Lot 16, Upper "v"

Distance from supply ditch meters	Depth cm	Texture	pH				HC, cm/hr				Change %/yr
			1965 Aug.	1967 Oct.	1969 May	1969 Sept.	1965 Aug.	1967 Oct.	1969 May	1969 Sept.	
76	0- 15	CL	8.0	8.0	7.8	8.0	.70	.38	.15	1.43	
	15- 31	SiCL	8.1	8.1	8.0	8.1	.43	.68	.30	.63	
	31- 61	SiCL + FS	8.3	8.3	8.2	8.3	.03	.03	.04	--	
	61- 92	SiCL	8.3	8.3	8.1	8.3	.03	.03	.04	--	
	92-122	SiCL	8.1	8.2	8.2	8.4	--	--	.04	--	
	122-153	SiCL	8.2	8.4	8.1	8.3	.03	.03	.06	--	
	153-183	SiCL	8.2	8.5	8.1	8.3	--	--	.04	--	
	Average		8.17	8.26	8.07	8.24	.174	.164	.096	.294	+69.0
260	0- 15	CL	8.0	8.1	8.0	8.0	--	--	.01	.13	
	15- 31	SiCL	8.1	8.2	8.2	8.1	.03	--	.01	.03	
	31- 61	SiCL-SiC	8.0	8.2	8.2	8.3	--	.03	.04	--	
	61- 92	SiCL-SiC	8.1	8.3	8.3	8.3	.03	--	.06	--	
	92-122	SiCL-VFSL	8.3	8.4	8.3	8.2	.05	.05	.03	--	
	122-153	SiCL-C	8.3	8.3	8.2	8.4	--	--	.04	.03	
	153-183	C	8.2	8.2	8.2	8.5	--	--	.03	--	
	Average		8.14	8.26	8.20	8.26	.016	.011	.031	.023	+44.0
Mean			8.16	8.26	8.13	8.25	.095	.088	.064	.159	+56.5
Deviation from the mean			.02	0	.06	.01	.079	.077	.033	.136	12.5

The data for the basins are presented in Figure 12 and Tables 3 and 6. Similar to lot 16, the upstream basins maintained a higher salinity level (EC 15.5 - 16.0 mmhos/cm, SAR 20.1 - 22.5, pH 8.16 - 8.20) than the downstream basins (EC 10.3 - 12.0 mmhos/cm, SAR 15.5 - 17.3, pH 8.07-8.11) while the HC's of the more elevated ones were less (.037 - .053 cm/hr) than those of the less elevated basins (.061 - .230 cm/hr). However, this difference between the salinities of the down and upstream basins diminished after 1967 due to a larger influx of salt (EC +8.3 %/yr) into the initially less saline downstream basins as compared to a very small influx of salts (EC +1.5 %/yr) into the initially higher saline upstream basins. In contrast, the SAR seemed to be reduced in general; the SAR of the downstream basins declined 5 %/yr, while that of the upstream basins increased only very slightly (SAR +1.4 %/yr). Hydraulic conductivities decreased more on the less elevated basins (HC -73.5 %/yr) as compared to the more elevated ones (HC -30.2 %/yr), while the pH increased a limited 0.5 %/yr for both regions. Because the EC and HC parameters in the field are more important with respect to plant growth than the SAR (Krogman and Milne, 1963), it was assumed that all basins deteriorated somewhat, especially those on the downstream end.

The initially higher salinity levels of the upstream basins was likely the result of a greater discharge of seepage water from the sand hills during the years previous to 1967. The subsequent resalinization of the area must have been caused by improper application of irrigation water and the lack of a dense, deep rooted plant cover.

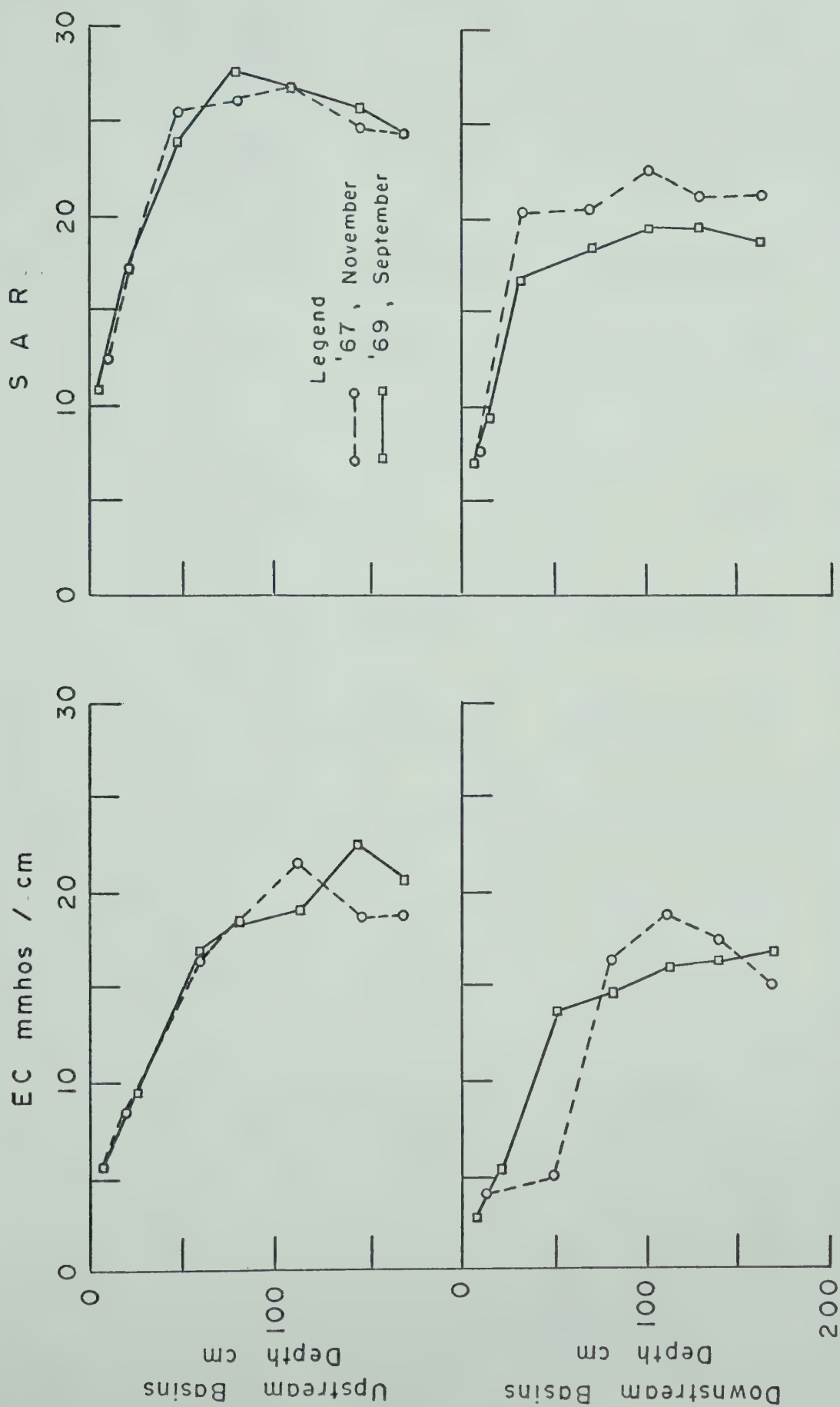


Figure 12. EC and SAR values of profiles of the upstream and downstream basins, Lower "V".

Table 6. pH and hydraulic conductivity values of Basins, Lower "V"

Location	Depth cm	Texture	pH				HC, cm/hr			
			1967 Nov.	1969 May	1969 Sept.	Change %/yr	1967 Nov.	1969 May	1969 Sept.	Change %/yr
Higher Basins (1 - 3)	0- 15	CL	8.0	8.1	8.0		.05	.06	--	
	15- 31	CL	8.0	8.1	8.0		.05	--	--	
	31- 61	VFSL	8.3	8.2	8.3		.08	.01	--	
	61- 92	SiCL + S	8.2	8.4	8.3		.03	.06	--	
	92-122	SiCL + S	8.2	8.2	8.3		.08	.12	.03	
	122-153	CL	8.1	8.3	8.3		.03	.20	.05	
	153-183	C	8.3	8.3	8.2		.05	.05	.18	
	Average		8.16	8.24	8.20	+0.5	.053	.071	.037	-30.2
Lower Basins (4 - 7)	0- 15	CL	7.8	8.0	7.9		.65	.05	.10	
	15- 31	CL	7.8	8.0	7.9		.65	.18	.05	
	31- 61	VFSL	8.1	8.1	8.2		.13	.03	--	
	61- 92	SiCL	8.2	8.3	8.1		.10	.03	--	
	92-122	SiCL + S	8.3	8.3	8.3		.10	.05	.18	
	122-153	SiCL + S	8.2	8.3	8.2		.08	.09	.05	
	153-183	C	8.1	8.0	8.2		--	.08	.05	
	Average		8.07	8.14	8.11	+0.5	.230	.073	.061	-73.5
Mean			8.12	8.19	8.16	+0.5	.142	.072	.049	-51.9
Deviation from the mean			.04	.05	.05	0	.088	.001	.012	21.6

The greater salinity increase at the lower basins resulted from the useage of smaller quantities and poorer quality of water. The drop in HC on both areas was likely caused by the dispersion and relocation of soil particles with a subsequent obstruction of the pores rather than a deflocculation phenomena.

From the above paragraphs, one could only conclude that the extent and rate of reclamation of each area was far from uniform. To compare the rates and uniformities of reclamation of the three areas, the average annual rate of desalinization and deviations from the means of the areas were determined and summarized. The rate of reclamation was expressed as a per cent change from the initial chemical and physical values of the soil and soil solution. The following summary, containing the average annual per cent of change, is based on Tables 3 to 6:

		Average annual per cent change			
		EC	SAR	pH	HC
Lot	9	-5.8	-2.1	-2.0	+10.4
Lot	16	-5.1	-3.2	+1.2	+56.5
Basins		+4.9	-3.2	+0.5	-51.9

This summary strongly indicated the salinization of the basins and also the very favorable desalinization of the border dike strips. The salinization and desalinization processes tended to follow closely high and low watertables, respectively (Figure 13). The above summary also indicated the deterioration of the HC in the basins in contrast to the improved HC of the border strips. Moreover the deviations from

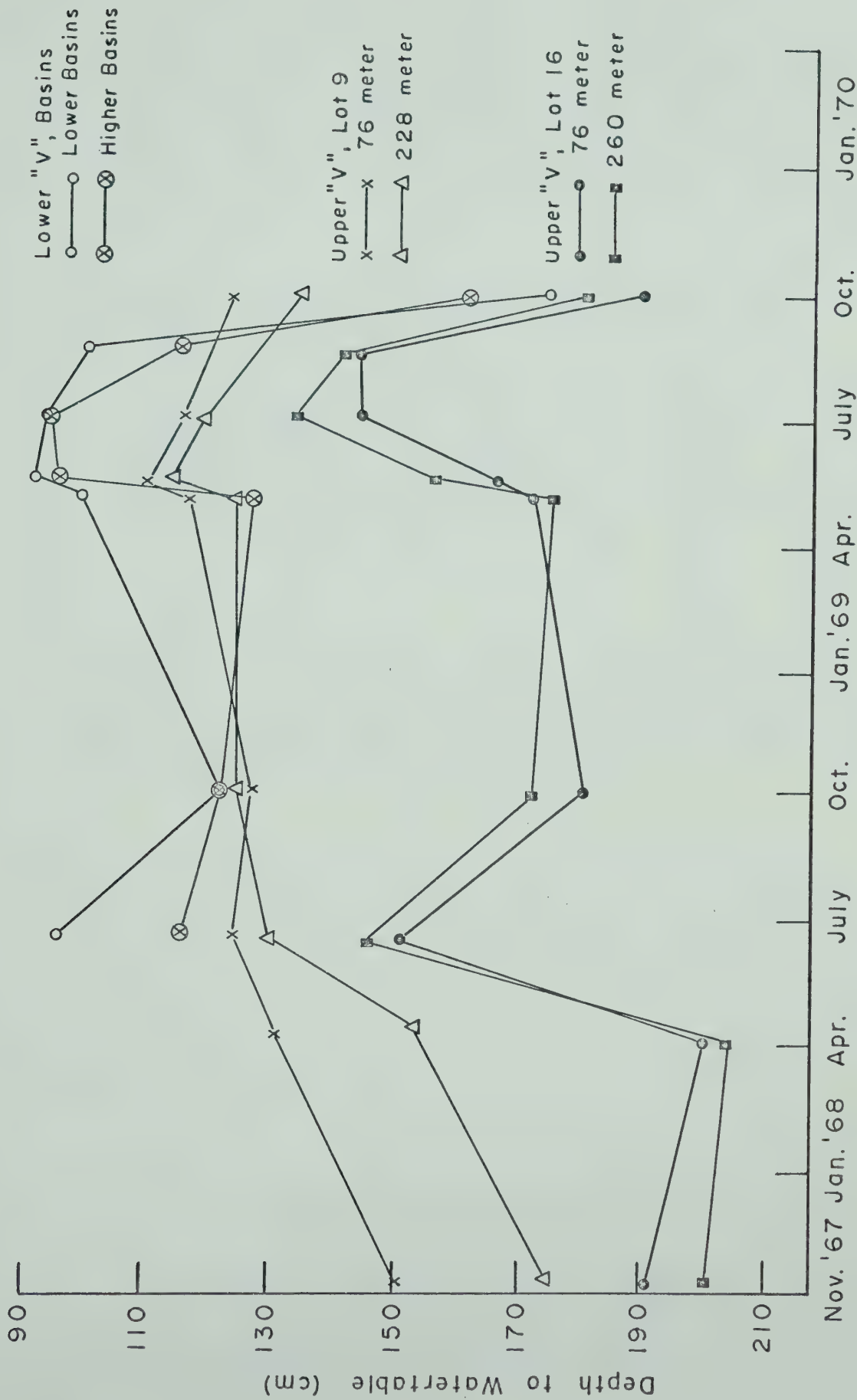


Figure 13. Groundwater levels of the Maple Creek, "V" projects.

the mean of each of the four parameters and the deviations from the mean of the per cent annual change of each parameter showed little uniformity in the basins. These deviations are indicated in the following summary of Tables 3 - 6:

Deviations from the mean of the upslope and downslope areas

	EC		SAR		pH		HC	
	Salt content mmhos/cm	Annual change in EC %	SAR	Annual change in SAR %	pH	Annual change in pH %	HC cm/hr	Annual change in HC %
Lot 9	4.2	+1.1*	3.0	+1.6	.06	+0.7	.01	+10.4
Lot 16	1.3	+0.6	3.3	+0.9	.01	+0.3	.10	+12.5
Basins	2.4	-3.4	2.4	-1.8	.05	0.0	.05	-21.7

* Note, that the positive (+) sign indicates that the change is directed toward increasing the deviation, and that for a negative (-) sign the opposite is the case.

Even though the changes of the four parameters on the basins were directed towards decreasing the disparity between the upslope and the downslope region, the general tendency of the basins to increase in EC and decrease in HC make it a less attractive reclamation method than the border dike system.

Hydraulic Conductivity Tests

After having determined the rate of reclamation in the field, a method was developed in the laboratory to speed up the reclamation.

To accelerate the reclamation earlier workers indicated that it was important to maintain a high permeability. Therefore the "area of stable permeability" had to be determined. The "area" in question is delineated by the "threshold" concentrations which are the concentrations related to a 20 per cent decrease in HC with respect to the HC of the high salt solution (800 meq/L) of the particular SAR series.

Figure 14 represents the HC graphs of the basic high salt solutions for each of the five SAR series. Equilibrium was obtained after approximately one pore volume of the SAR 8, 18, and 30 leachants, and two pore volumes of the SAR 46 and 70 leachants had passed through the soil. The high SAR values had strangely enough initially the highest HC, and maintained this position, even though the reduction in HC here was larger than for soils leached with solutions of lower SAR. The equilibrium HC values were .034 cm/hr for SAR 70, .029 cm/hr for SAR 46, .027 cm/hr for SAR 30, 0.022 cm/hr for SAR 18, and .019 cm/hr for SAR 8. A second test, similar in character to the previous one, provided identical results; again high HC values coincided with large SAR values of the leachants and low HC's coincided with small SAR values.

The HC values shown in Figure 14, which were opposite to what normally could be expected, were thought to be the result of increasingly larger amounts of illuviated sodium in the lower portion of the soil profile in the case of treatments with solutions of low SAR. Figure 15 showed that the leachates initially had greater SAR values if their corresponding leachants were of a low SAR. To check if corresponding SAR increases did occur in the soil solution of the lower portion of the soil profile, a similar soil was leached with a

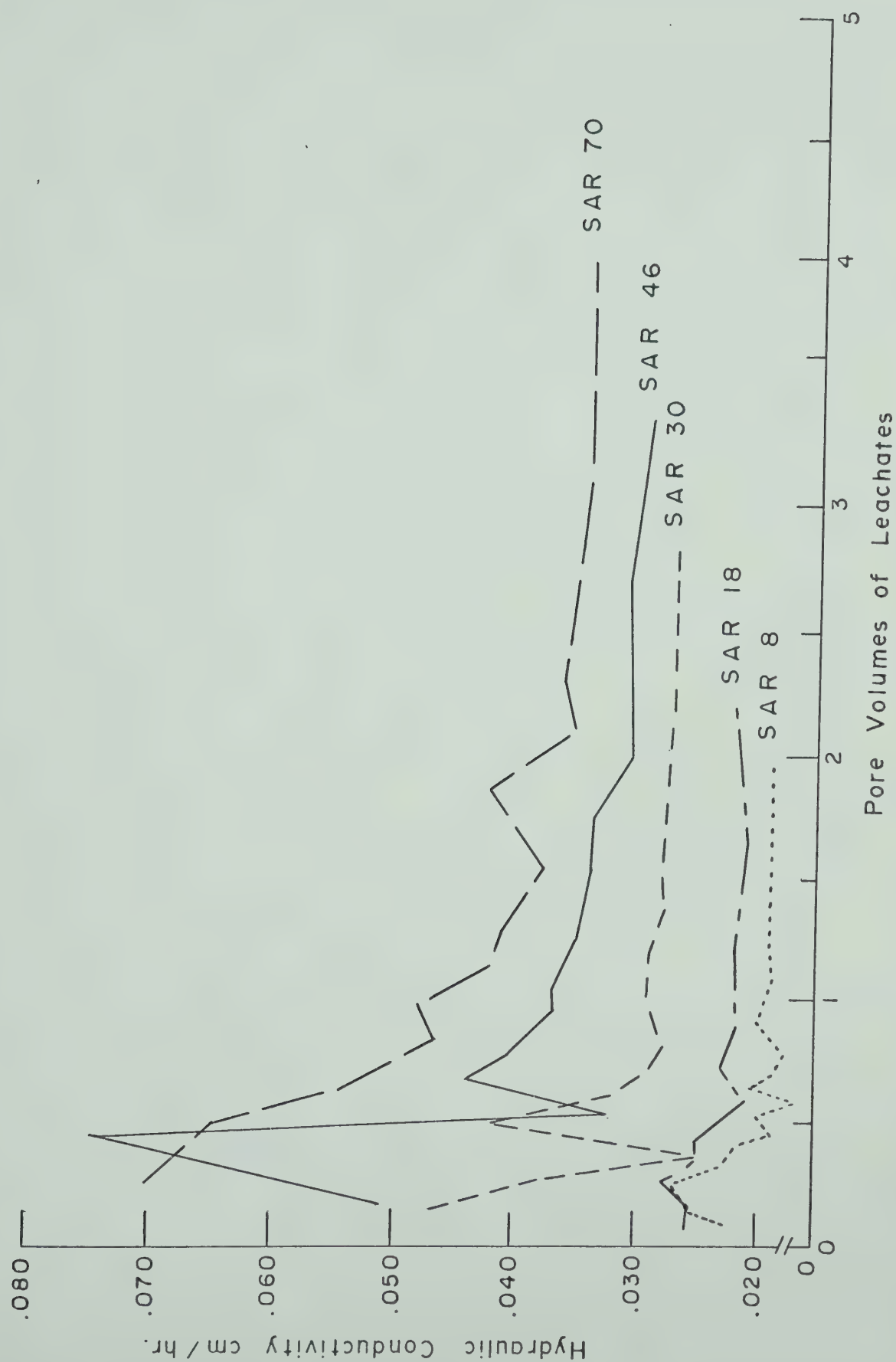


Figure 14. Hydraulic conductivity values of the soil when treated with 800 meq/L solutions of the various SAR series.

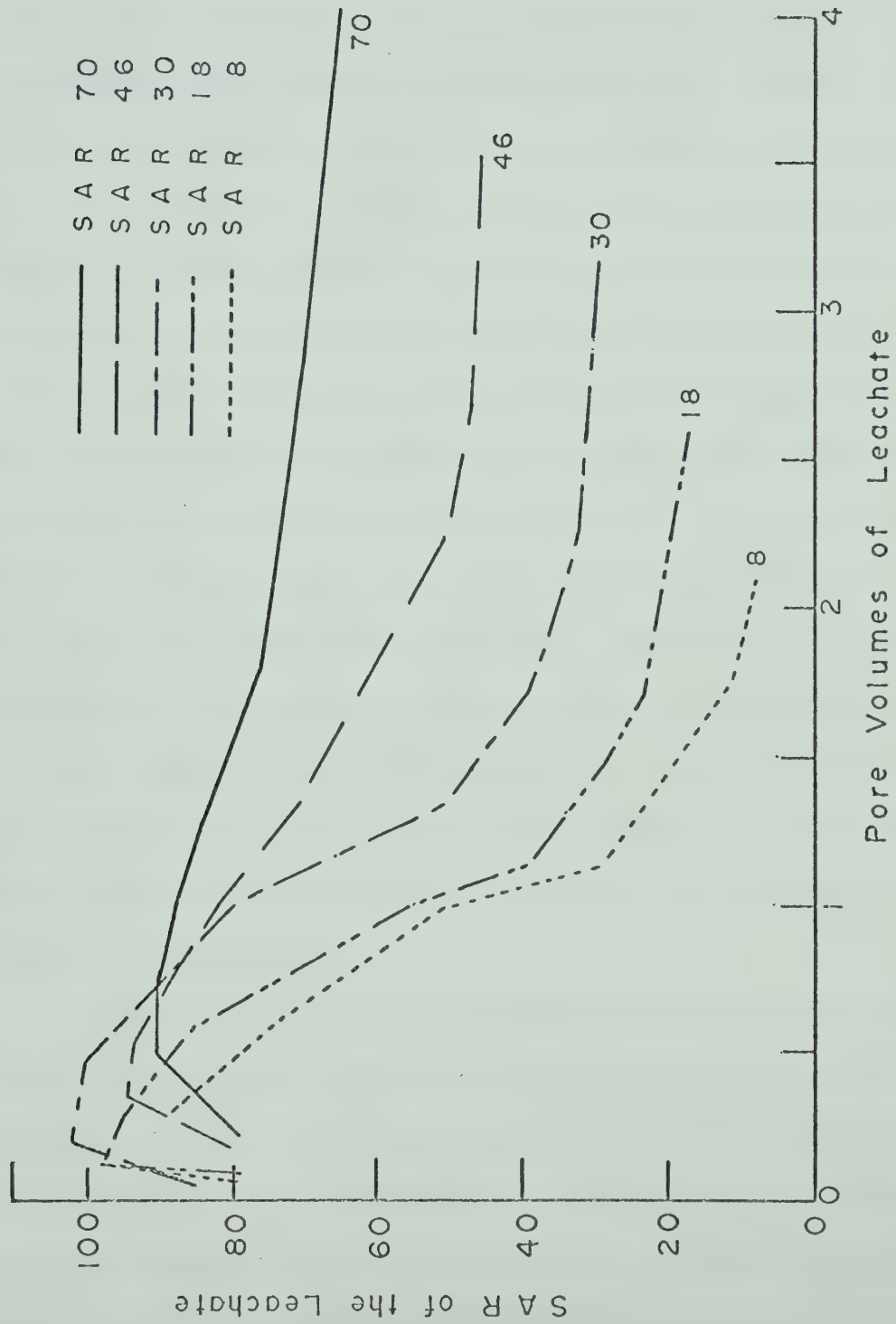


Figure 15. SAR values of the leachates from the 800 meq/L leachant at various SAR's.

SAR 8 and 800 meq/L solution. After the first, second, and third pore volume of leachant passed through the soil, the leachates and then the upper and lower halves of the soil profile were analyzed. Again the SAR values of the leachates were high initially. However, the SAR's of the soil solutions of both portions decreased from their initial value of SAR 42.2, although that of the lower portion reduced initially less rapidly (Figure 16). This apparent inconsistency between the SAR of the soil solution and of the leachate resulted possibly from the lack of an adequate number of SAR values of the soil solution during the leaching with the first pore volume (Figure 16). Nevertheless, a fair amount of evidence pointed to an initial increase of SAR in the lower portion of the soil. According to Reeve and Doering (1966) such initial unfavorable conditions, regardless of how short-lived they are, do bring about lasting irreversible detrimental effects to the soil's permeability. Furthermore, the increasing amount of precipitated gypsum in the conducting pores (Figure 17) following leachings with low SAR solutions contributed to the impedement of the permeability of the soil.

The first HC reduction, during the treatment with the high salt solutions (800 meq/L) resulted partly from the deflocculation of Na saturated colloids. Additional decreases in HC were caused by the obstruction of pores with dispersed soil particles and air bubbles. According to Doering (1965) the latter reductions constitute about 20 to 30 per cent of the total HC reduction obtained.

Following these reductions, further decreases in HC resulted when solutions with lower EC's were used as leachants.

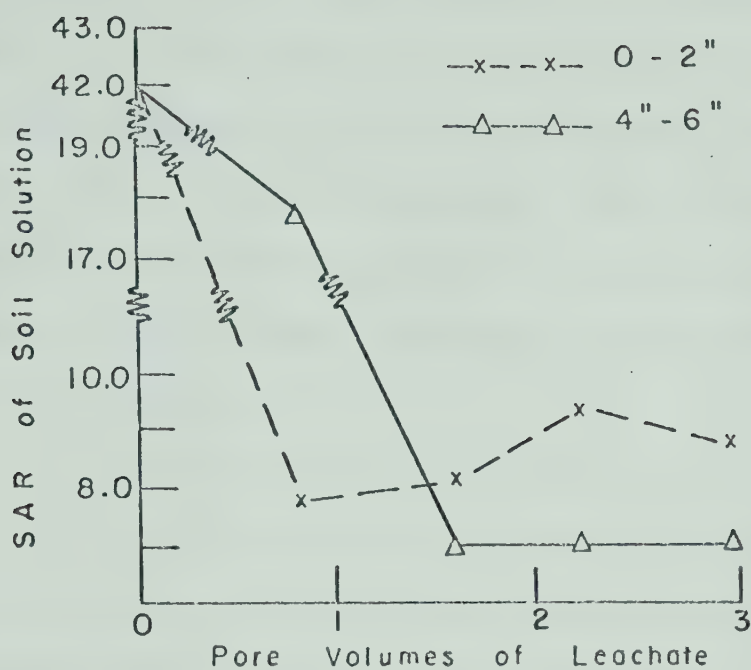


Figure 16. SAR values of soil solutions from the upper and lower portions of a profile treated with 800 meq/L SAR 8 solution.

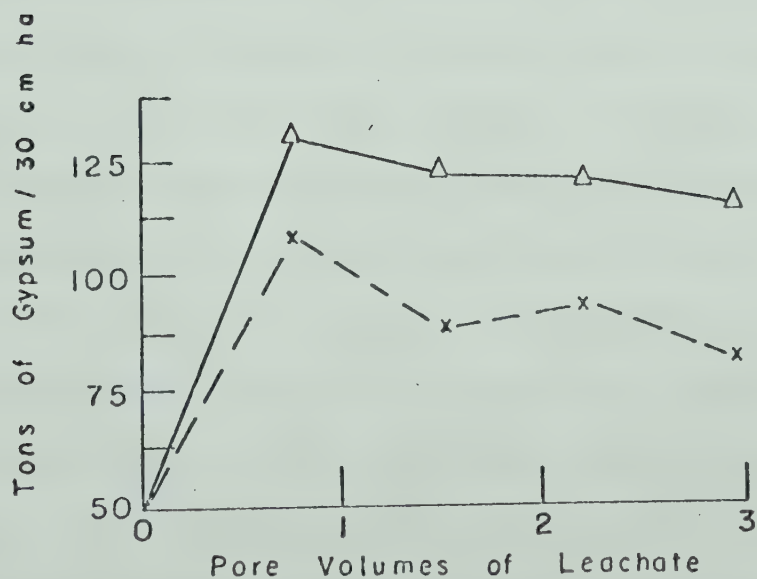


Figure 17. Amounts of gypsum in the upper and lower portions of a profile treated with 800 meq/L SAR 8 solution.

Figures 18 to 22 show the HC's of each SAR series at their reduced EC values. The 500 and 300 meq/L leachants failed to decrease the HC from that of the high salt solution. However, increasingly lower EC's in the leachants caused increasingly lower HC values in general. Simultaneously, the HC's decreased even more at high SAR's; quite in contrast to what happened during the leaching with the 800 meq/L solutions (Figure 14).

From the HC reductions between the first and second equilibrium and the first and third equilibrium, the percentages of HC decreases were calculated. The HC reductions were placed over the equilibrium HC's of the high salt solution of the particular SAR series, and then multiplied by 100. Figure 23 presents the per cent HC decreases. The HC reduced most rapidly between 300 and 30 meq/L. In this range of EC values the "threshold" concentrations were located, corresponding to a 20 per cent HC decrease, as explained earlier. A 20 per cent HC reduction was chosen because it formed the mean between the 15 per cent HC decrease of Quirk and Schofield (1955) and the 25 per cent HC decrease of Doneen (1961). Consequently the "threshold" concentrations for our soil became 330, 123, 123, 69, and 53 meq/L for SAR's 70, 46, 30, 18, and 8, respectively (Figure 24). These concentrations proved to be about 10 times larger than those obtained by Graveland (1960) for heavy Solonetzic soils in Alberta.

The chemical status of our original soil placed the permeability of this soil inside the "area of stable permeability" (Figure 24). Therefore, when treated properly, this soil could maintain a high

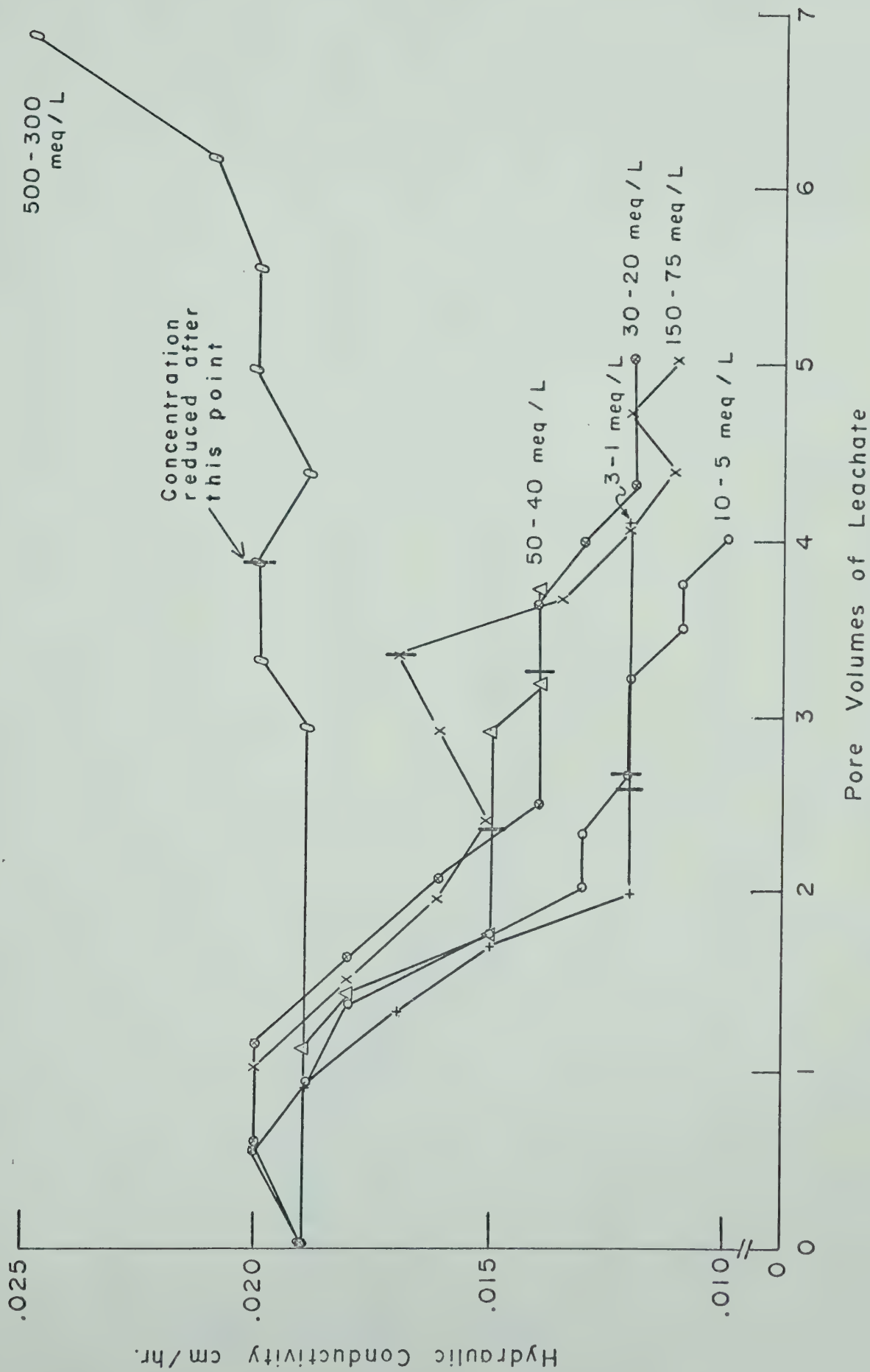


Figure 18. HC values during the treatment with solutions of SAR 8.

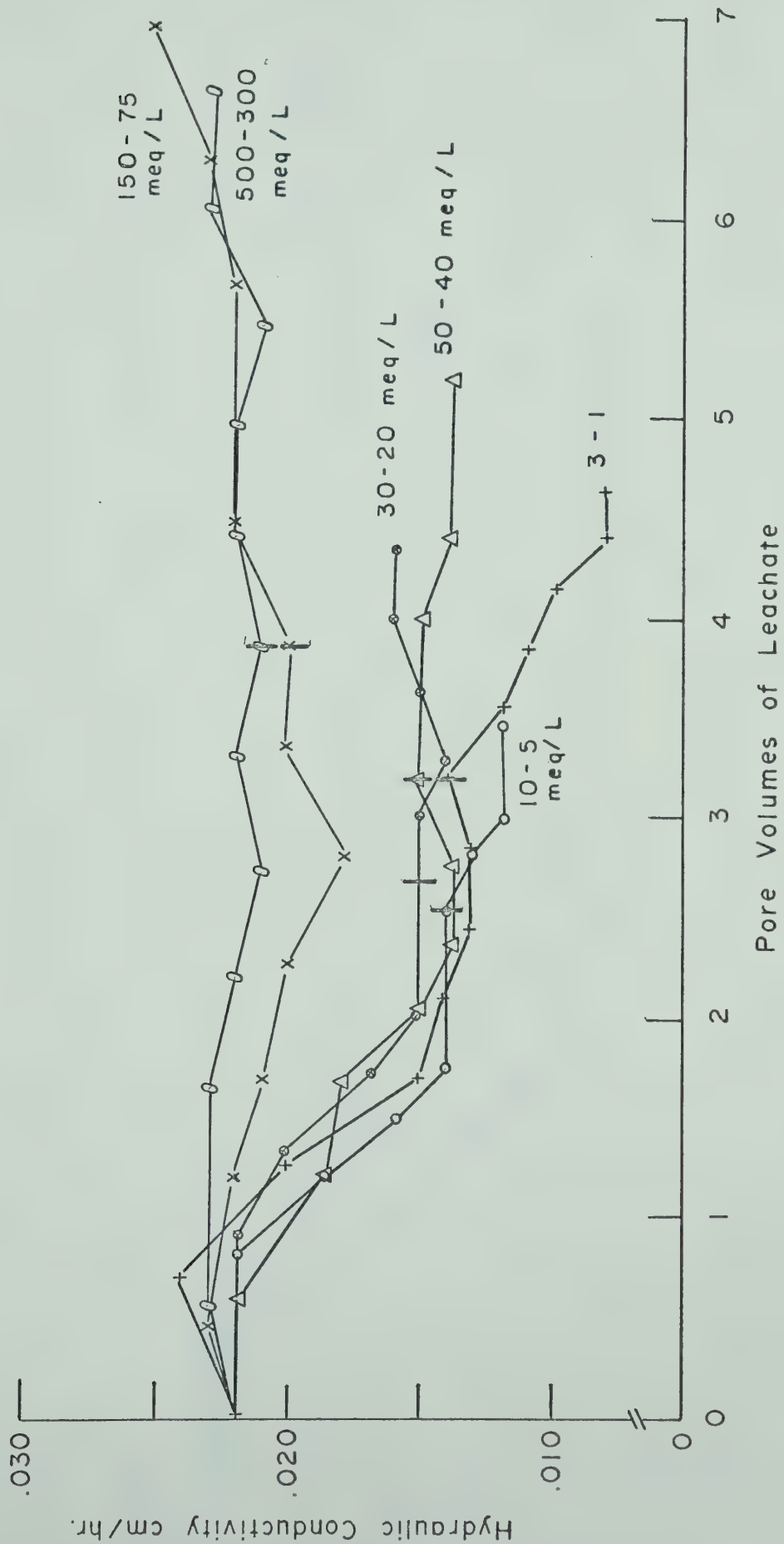


Figure 19. HC values during the treatment with solutions of SAR 18.

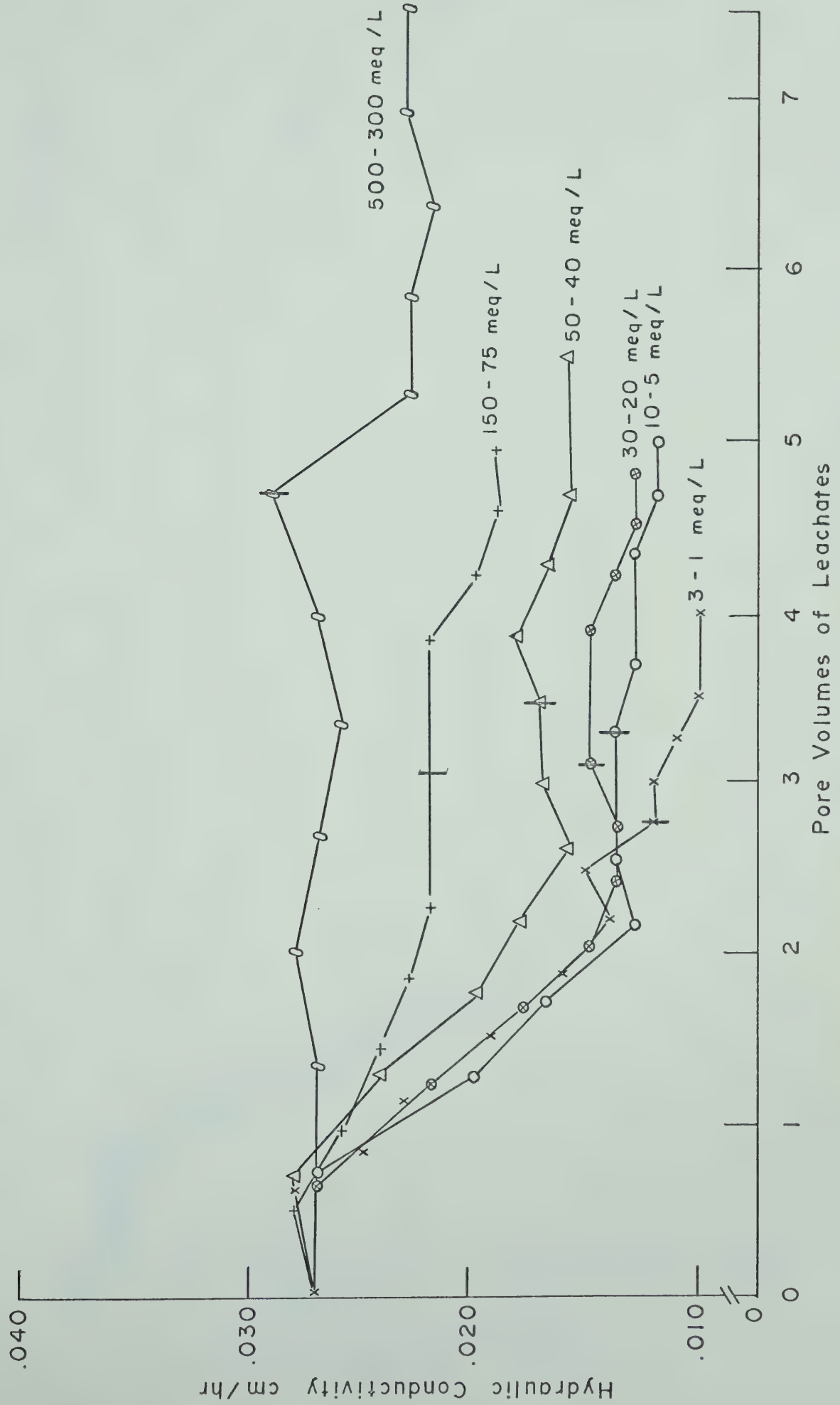


Figure 20. HC values during the treatment with solutions of SAR 30.

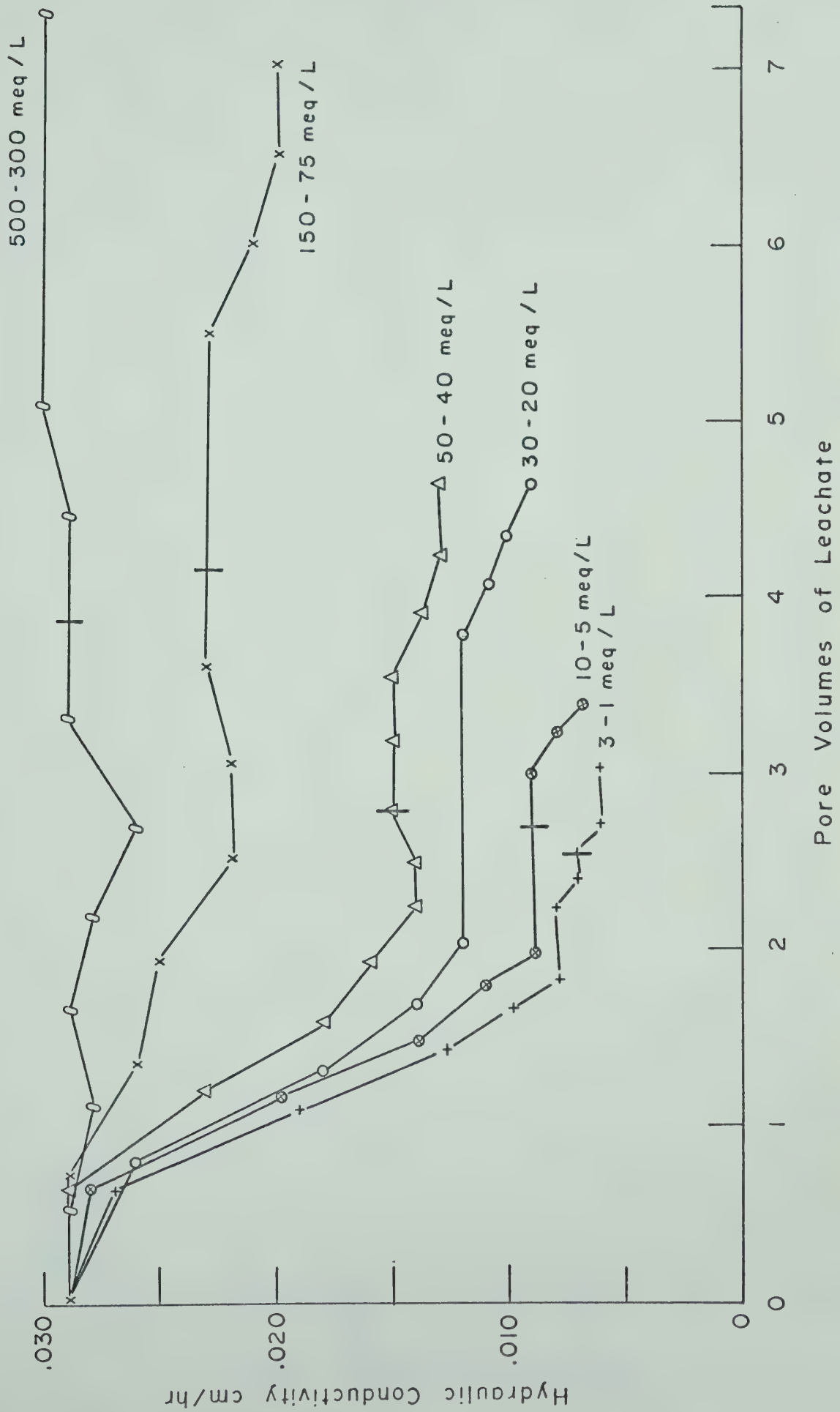


Figure 21. HC values during the treatment with solutions of SAR 46.

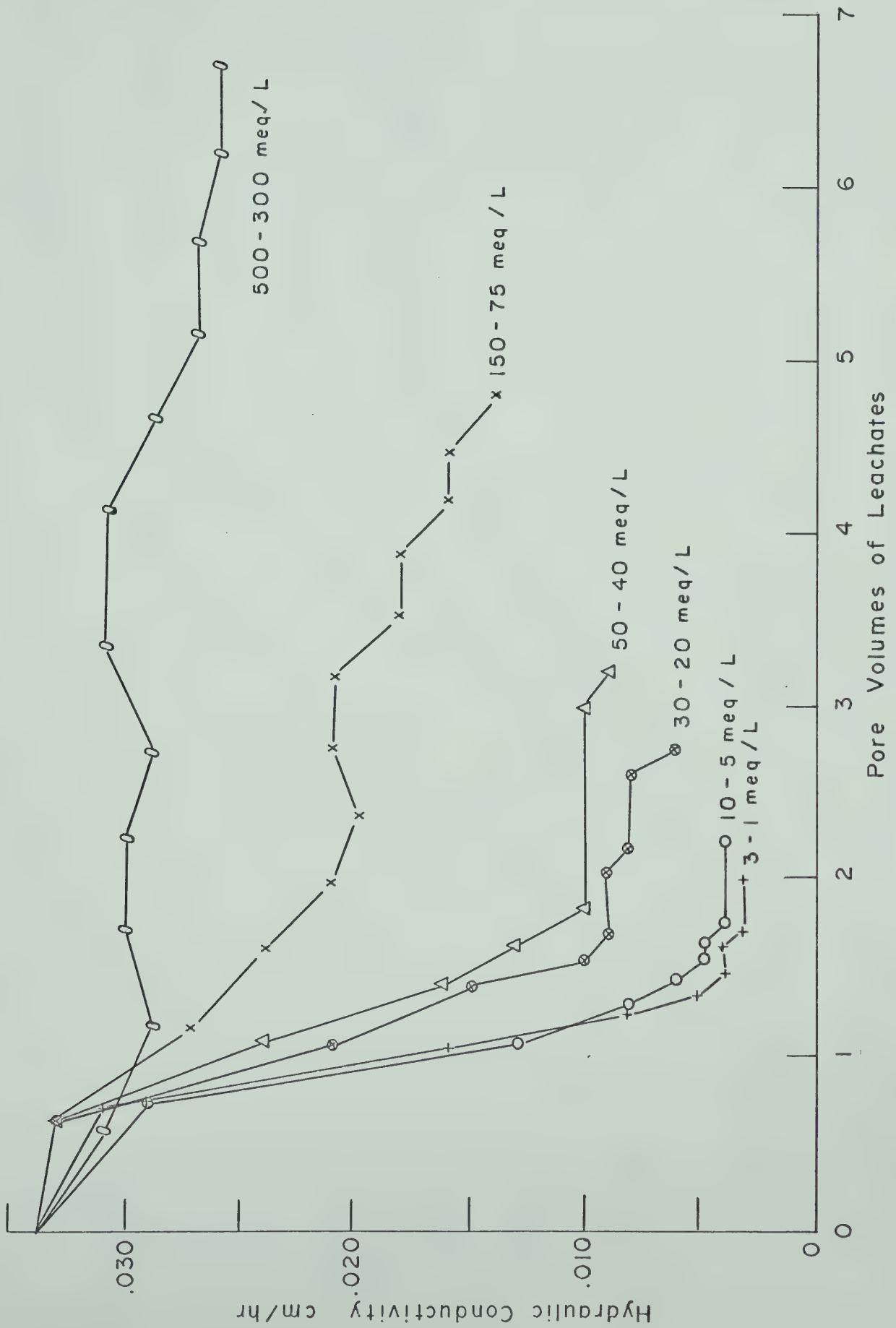


Figure 22. HC values during the treatment with solutions of SAR 70.

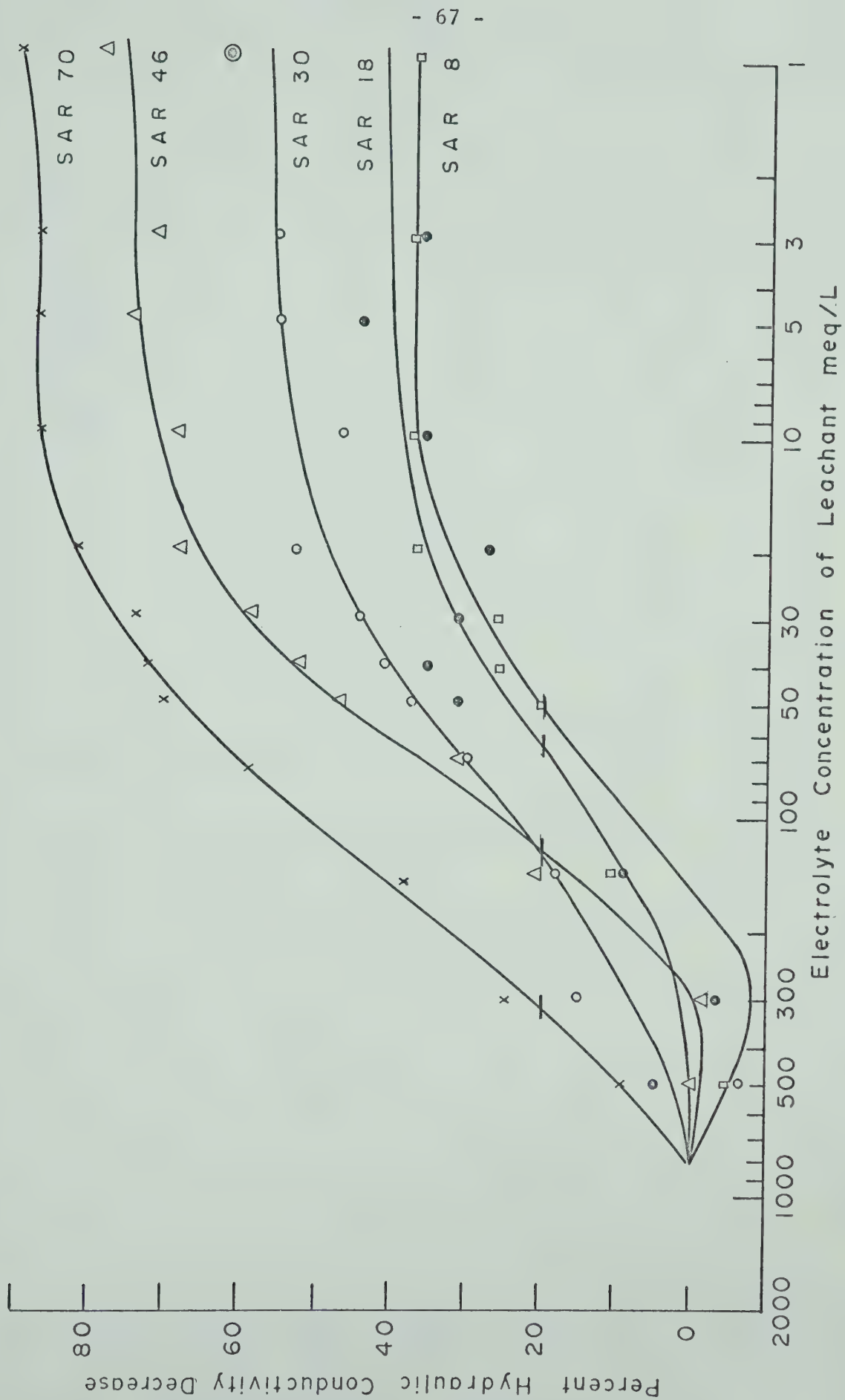


Figure 23. Per cent HC decreases in the soil of the Maple Creek "V" projects.

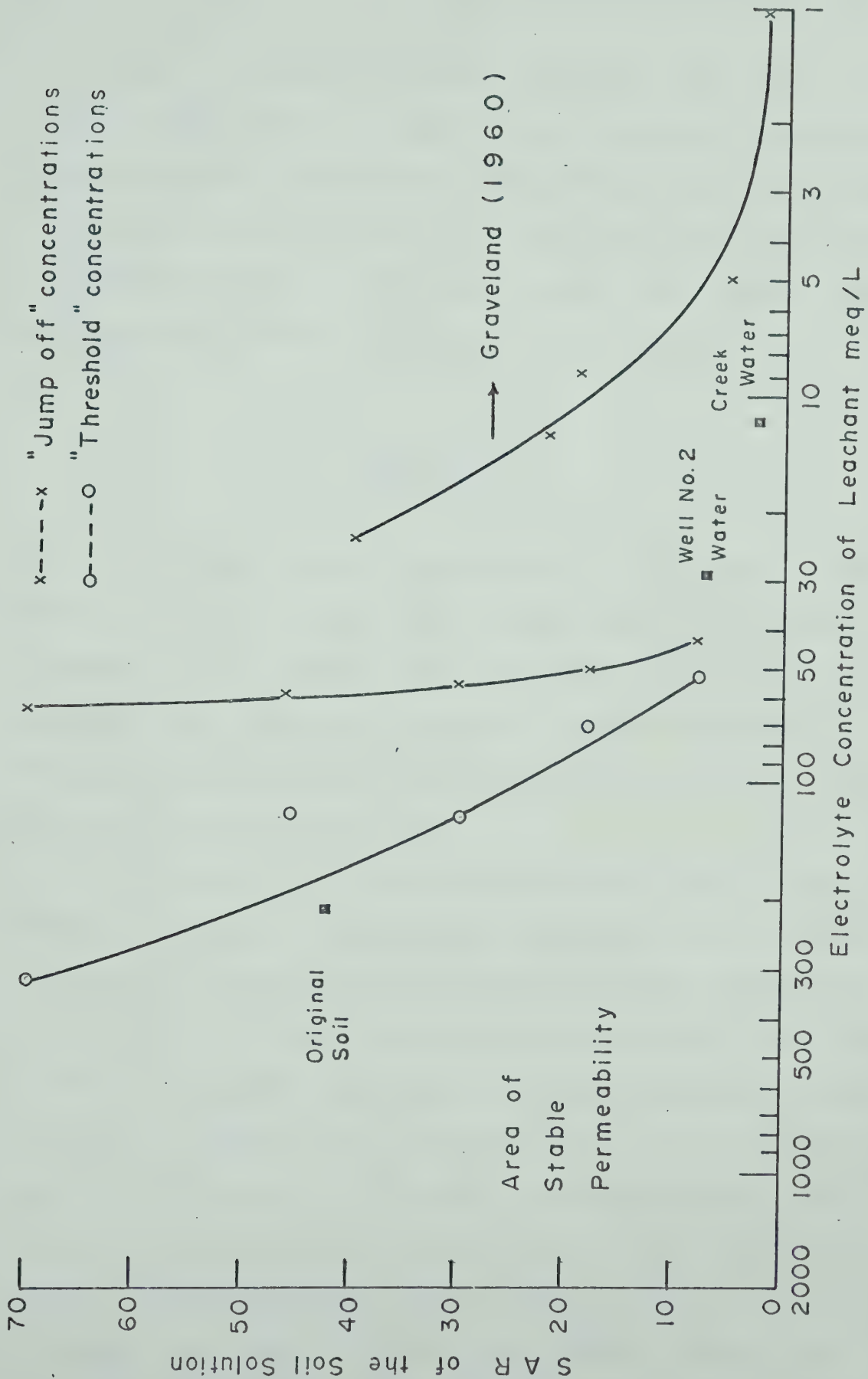


Figure 24. "Threshold" and "jump-off" concentrations of soil of the Maple Creek "V" projects, and "threshold" concentrations determined by Graveland (1960).

permeability. As Figure 24 indicates, well No. 2 and creek water both contained insufficient amounts of salt to maintain the chemistry of the soil in the "stable area". Consequently, unless the boundaries of the "area of stable permeability" proved to be wrong, amendments would have to be added to both water supplies. The "jump-off" curve in Figure 24 is referred to in the following section.

Swelling Tests

With the "jump-off" concentrations, it was hoped to confirm and more accurately delineate the boundary of the "area of stable permeability". To establish these "jump-off" concentrations, the swelling values of the soil at various EC and SAR values had to be determined. Swelling values were defined as the weight of absorbed water in grams, per gram of clay.

Figures 25 and 26 present the swelling values for the various EC-SAR combinations. It may be noted that the pH used was 7 and 4, respectively. The swelling values of our soil at pH 7 (Figure 25) proved to be 5 to 10 times larger than those obtained by Rowell (1969). A finer texture (SiCL) and a higher percentage of montmorillonite in our soil, as compared to the SCL soil of Rowell, which contained 80 per cent illite, accounted for the greater swelling in our soil. The reduced swelling in our soil upon treatment with pH 4 solutions (Figure 26) resulted probably from the increased positive charge at the edges of the crystal lattices (Rowell, 1965). However, for simplicity and the fact that the permeability tests were carried out

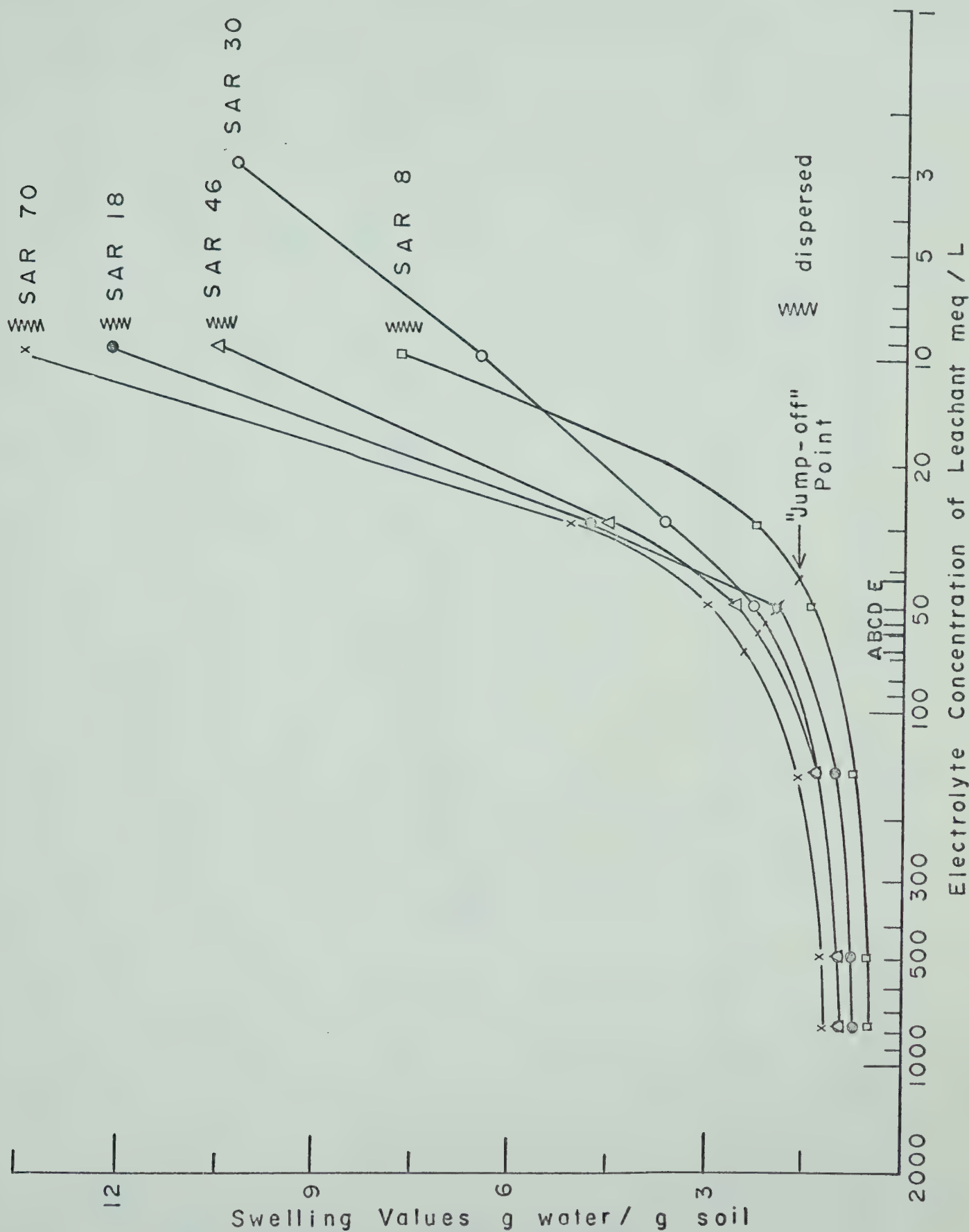


Figure 25. Swelling values of the Maple Creek "V" projects' soil after treatment with solutions of various SAR's and EC's, and pH 7.

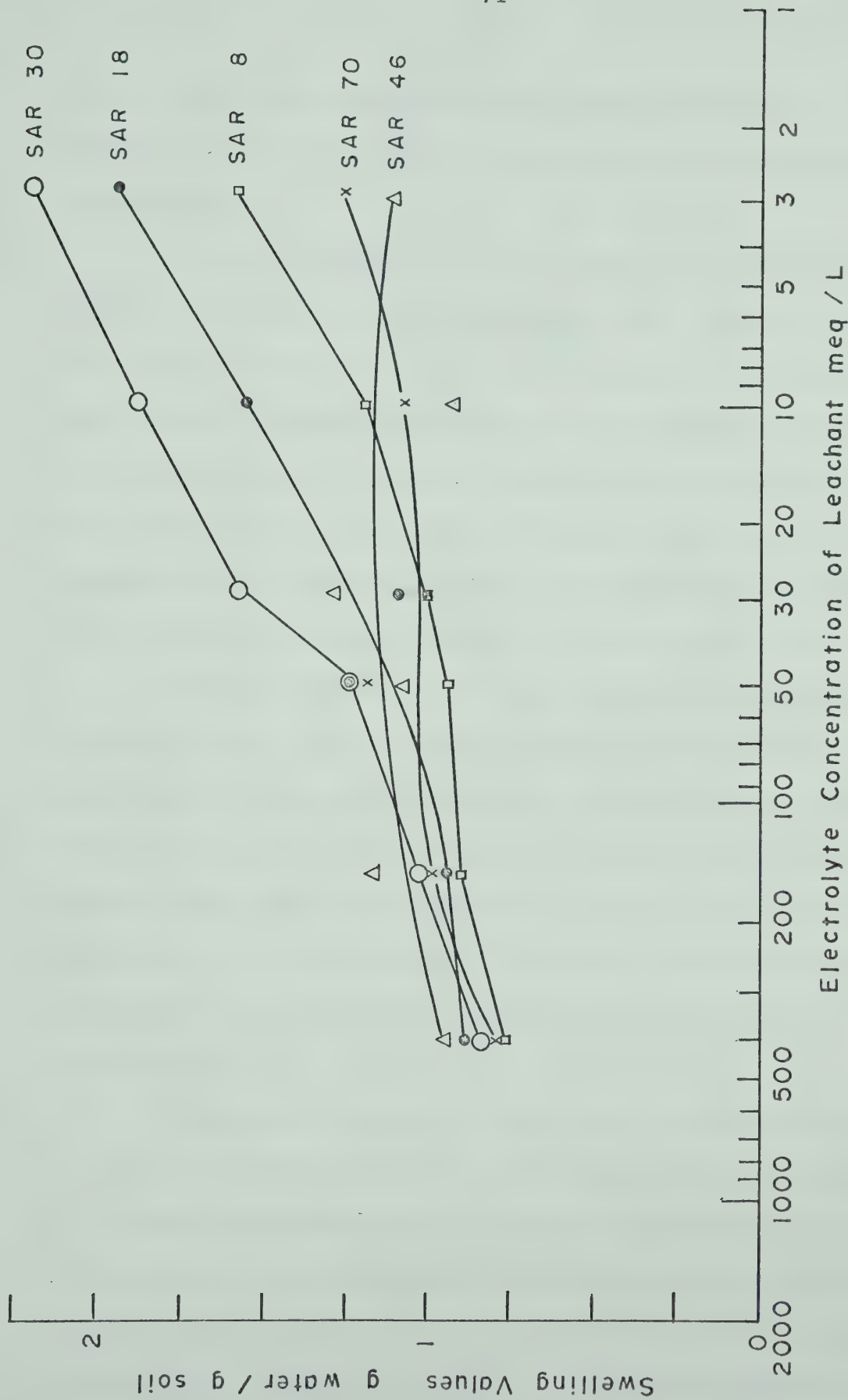


Figure 26. Swelling values of the Maple Creek "V" projects' soil after treatment with solutions of various SAR's and EC's, and pH 4.

with pH 7 solutions, only the swelling values produced by the pH 7 solutions were considered for the determination of the "jump-off" concentrations.

Figure 25 indicates that the largest swelling values were obtained by the solutions with the highest SAR. However, all treated soils showed accelerations in the amount of swelling between the concentrations of 300 meq/L and 30 meq/L of the leachants. Consequently, in the latter range the "jump-off" points would have to be located. These points were the projections of the "jump-off" points, as is explained earlier (page 18). Figure 25 indicated the five "jump-off" points and their respective "jump-off" concentrations A - E.

The resulting "jump-off" curve was presented in Figure 24. It indicated that at low SAR, the "jump-off" and "threshold" concentrations were close together; however, at high SAR values the two concentrations varied considerably. Consequently the "jump-off" concentrations, rather than confirming, cast doubt over the exact delineation of the "stable area". Therefore, to be safe, the "threshold" concentrations were maintained as boundaries for the "area of stable permeability".

Having established the "stable area", leachants could be selected which would maintain the optimum permeability of the soil. Very likely these leachants would return the highest net profits for the artificial reclamation process because the speedier reclamation would bring about savings in labour and solution, and furthermore, additional crop revenues. To prove or disprove the hypothesis that the most efficient leachant might be located in the "stable area"

and simultaneously determine its profit, the extra crop revenues and the costs of reclamation had to be determined for all levels of desalinization of the soil.

Greenhouse Study

From a consideration of the crops grown on unreclaimed and partially reclaimed soil, the extra crop revenues resulting from reclamation could be determined. Table 7 presents the germination and yield data of the two crops at various levels of desalinization of the soil. The germination of barley and alfalfa, especially alfalfa, was considerably delayed at EC values from 4.5 to 10 mmhos/cm while between 10 and 12 mmhos/cm, growth was inhibited altogether. On the other hand, SAR did not seem to affect the germination of either one of the two crops.

The yields of barley and alfalfa increased rapidly with reductions in EC (Table 7). Table 7 depicts a tendency for the yields of alfalfa to rise with increases in SAR and Figure 27 shows a similar trend for yields of barley at constant EC levels. For a particular EC value, the largest barley crop was obtained at its highest SAR. Nevertheless, maximum barley yields occurred at simultaneously low EC and SAR values. Possible reasons for the beneficial influence of the SAR could be the stimulating effect of sodium at low concentrations (Pearson and Bernstein, 1958).

To determine the revenues from additional yields over and above those of the checks as a result of the artificial reclamation,

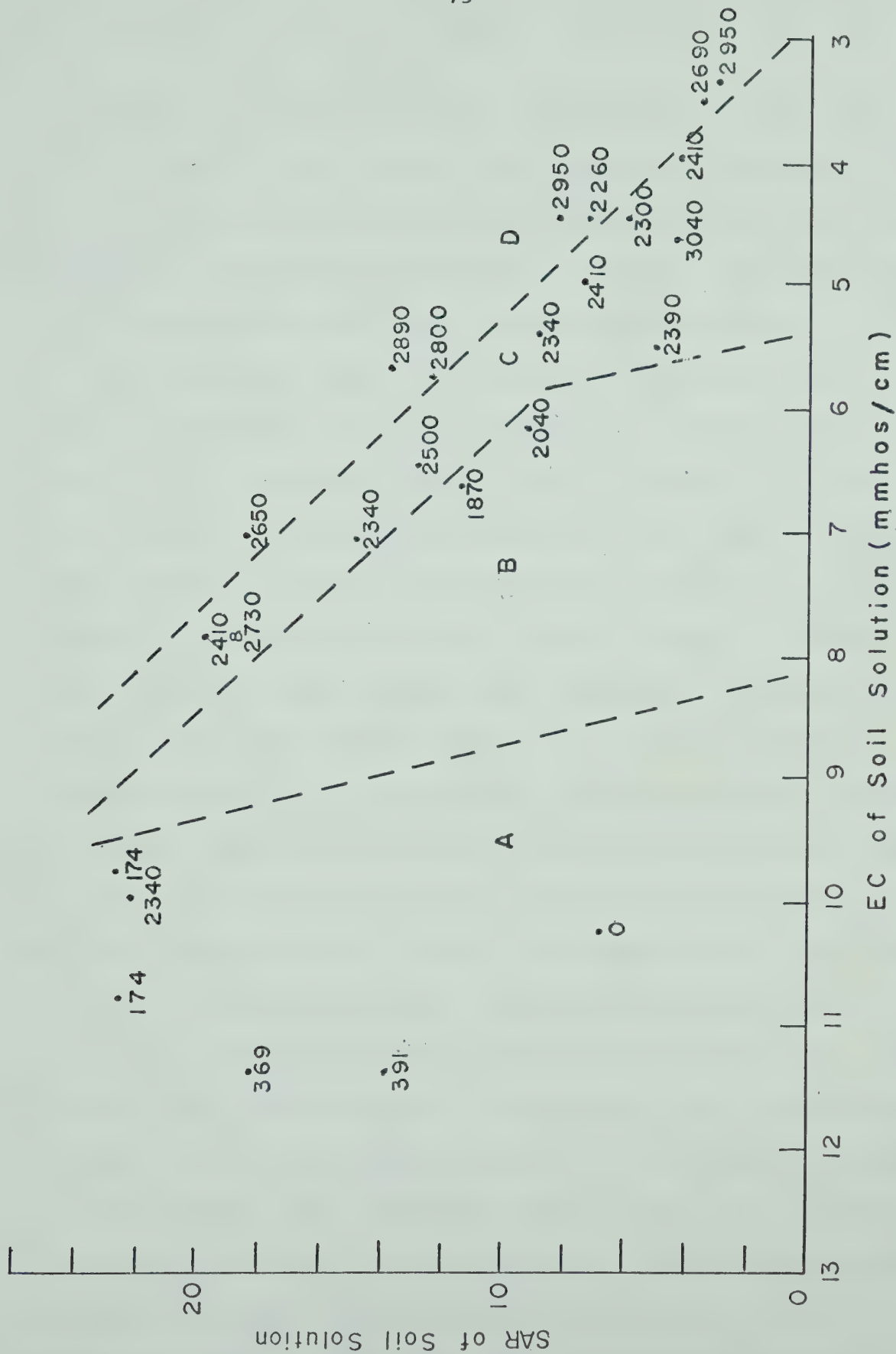


Figure 27. Calculated barley yields on Maple Creek "V" projects at various salinity levels (kg/ha) with groupings of yields into four categories.

the yields per pot were converted to comparable field yields and the various salinity levels along with their estimated yields determined. For this purpose the top growth in the laboratory of 12.05 g/pot was assumed to be equivalent to 3,040 kg/ha (57 bu/ac). The field yields for the other salinity levels were found by multiplying their g/pot by 3,040/12.05 kg/ha (Table 7). These field yields were plotted in Figure 27 and divided into four groupings: group A, < 500 kg/ha; group B, 500 - 2,000 kg/ha; group C, 2,000 - 2,500 kg/ha; and group D, $> 2,500$ kg/ha. To approximate the various salinity levels during the natural reclamation, it was assumed that the rate and manner of desalinization in the field would be quite similar to those in a laboratory experiment, if the field conditions were optimum for reclamation, and both were leached with similar solutions (No. 2 well water). Figure 28 indicates the EC and SAR curves for the laboratory experiment. Each curve is the average of the results obtained using two solutions (#3 and #4) which were comparable to well water No. 2 (2.3 mmhos/cm and SAR 7.1). Initially there is a rapid desalinization which tapers off near the end. Optimum reclamation conditions existed on the upslope end of lot 9, Upper "V", which was leached with well No. 2 water. It produced rates of reclamation of .87 mmhos/cm/yr at EC 9 mmhos/cm, and 1.07 SAR/yr at SAR 23.5, which corresponded in both cases to .18 pore volume of leachant passing through the soil. Consequently, annual rates of reclamation at various levels of desalinization were assumed to be the amount of change in EC and SAR during the passage of .18 pore volume of leachant. On each curve this estimated annual decrease in EC and SAR has been marked.

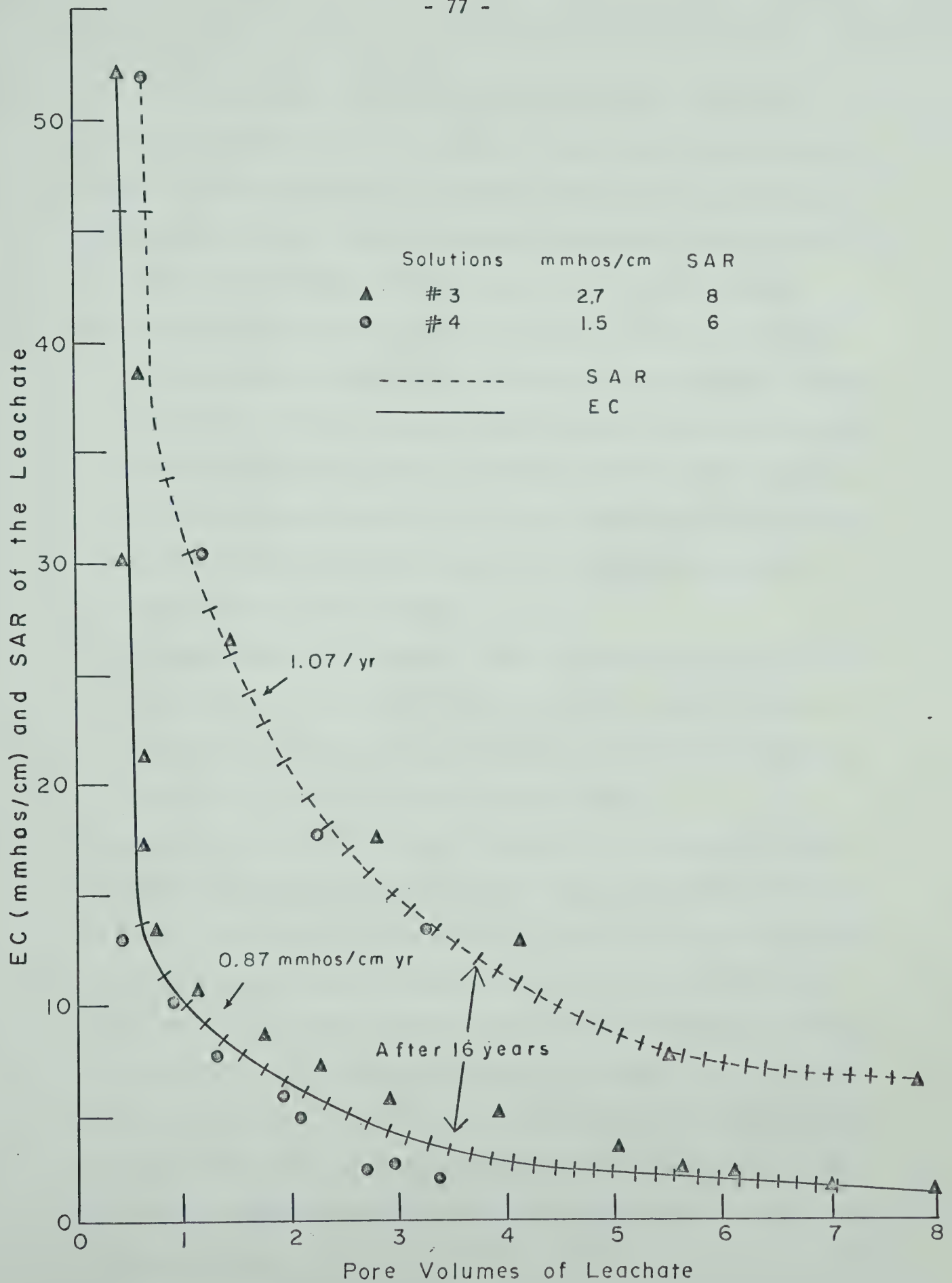


Figure 28. EC and SAR values of leachates from Maple Creek "V" projects' soil treated with #3 and #4 solutions.

Crop yields related to the salinity levels for natural reclamation in the field over a period of years were estimated from Figures 27 and 28 and Table 7 as shown in the following example:

1. For salinity level SAR 14.8 and EC 7.0 mmhos/cm, the yield was determined from Figure 27 and estimated to be \pm 2,300 kg/ha.
2. The following year the salinity level had decreased as a result of the natural reclamation and consequently the yield did increase. The salinity level had become that of the previous year minus one interval (Figure 28), and as such became SAR 14 and EC 6.3 mmhos/cm. The corresponding field yield read from Figure 27 was 2,400 kg/ha. Salinity levels and yields for subsequent yields were estimated in a similar manner.
3. The determination of salinity levels and their yields was continued until the most saline soil (SAR 45.1, EC 25.5 mmhos/cm) obtained annual yields of well over 2,500 kg/ha, and this was estimated to occur after 16 years in this particular case.

For each salinity level the yields during these 16 years were added. The difference between the total yields of the unreclaimed (check soil in Table 7) and partially reclaimed soil (any of the treated soils in Table 7) indicated the extra crop yields resulting from artificial reclamation. Multiplying the extra crop yield by \$2.95/100 kg, which was the market price of \$3.10/100 kg for barley minus the storage and trucking charges of \$0.15/100 kg, the extra revenue for each salinity level was found (Table 7). To determine the net profit, the cost of artificial reclamation was subtracted from these extra revenues. This is discussed below.

Costs of Reclamation

The costs of artificial reclamation to the various desalinization levels included the combined charges for water, amendments, and labour. To determine the lowest total cost of reclamation to each salinity level, three important steps were required. First, all possible routes of desalinization to each salinity level had to be determined, based on the analyses of the leachates. Secondly, the cost of labour, water, and the most efficient amendment had to be found. Thirdly, the total cost for water, amendment, and labour had to be determined for each route, in order that the least expensive route to each salinity level could be selected.

1. Leachate analysis

To determine the possible routes along which a soil could be desalinized to a specific salinity level, the leachates of each of the treated soils in the HC tests were analyzed for EC and SAR. Leaching with the highly saline 800 meq/L solution with the various SAR's resulted in near-perfect equilibration of the EC and SAR of the leachates with the leachants (Figures 29 and 15). The EC of the leachate, however, ran 10 mmhos/cm lower than the anticipated EC value of the leachant which had been calculated from a formula $\text{meq/L} = 10 \times \text{EC}$. Possibly the factor of 10 was incorrect and should have been replaced by 11.4, even though for chlorides a factor lower than 10 is normally assumed.

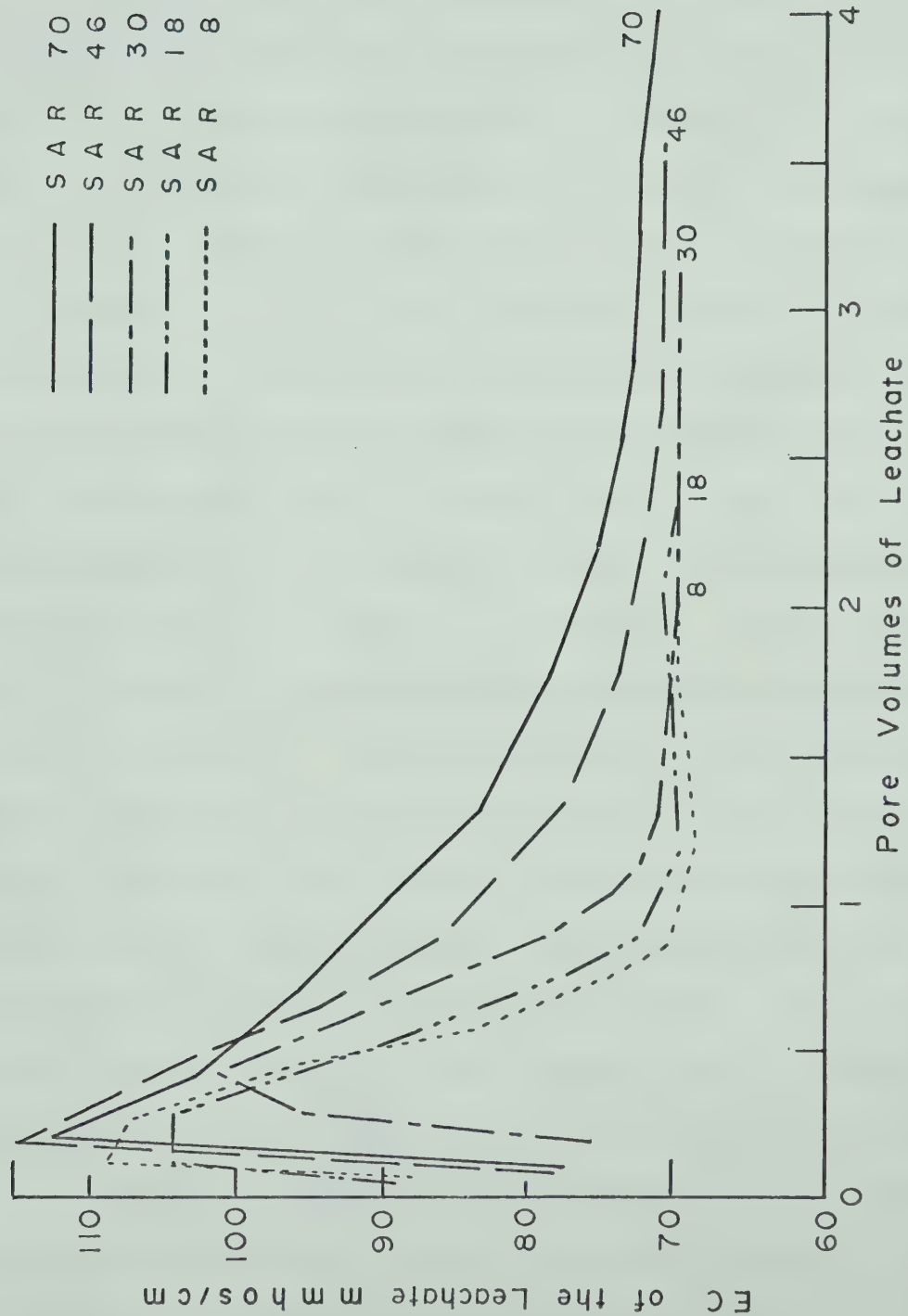


Figure 29. EC values of the leachates from 800 meq/L leachants at various SAR values.

During the second and third leachings with the less saline leachants and especially with the 3 - 1 meq/L leachant (Figure 30), the soil solutions were unable to equilibrate with the leachants. The 500 meq/L leachant formed an exception, after three pore volumes the EC of the leachate had pretty well levelled out at 50 mmhos/cm (Figure 31). Using the equation $\text{meq/L} = 10 \times \text{EC}$, the 50 mmhos/cm in the leachate amounted to 500 meq/L, a figure quite similar to that of the leachant. The 3 - 1 meq/L solutions produced a very rapid initial drop in the EC of the leachates, but no equilibrium, during the second leaching and only a tardy levelling off of the EC during the third leaching (Figure 30). In general, the EC values of the leachates remained above those of the leachants with the highest SAR solutions producing the highest EC values in the leachates. For all concentrations of leachants the highest SAR leachants produced the highest EC values in the leachates. These higher EC values in the leachates as a result of leaching with a high SAR solution could be caused by the decreased eluviation of salts and the increased solubility of the abundant amount of CaSO_4 in the soil. A similar phenomenon must occur with a decrease in the salt content of the leachate. This would explain the higher than expected EC's in the leachates from 3 - 1 meq/L solutions, and the less than expected EC's from the 800 meq/L leachants.

The SAR's of the leachates dropped in general far below the expected equilibrium values (Figures 32 and 33). The least saline (3 - 1 meq/L), high SAR (70) leachants, produced leachates of which the SAR kept dropping continuously (Figure 32). Again this must have

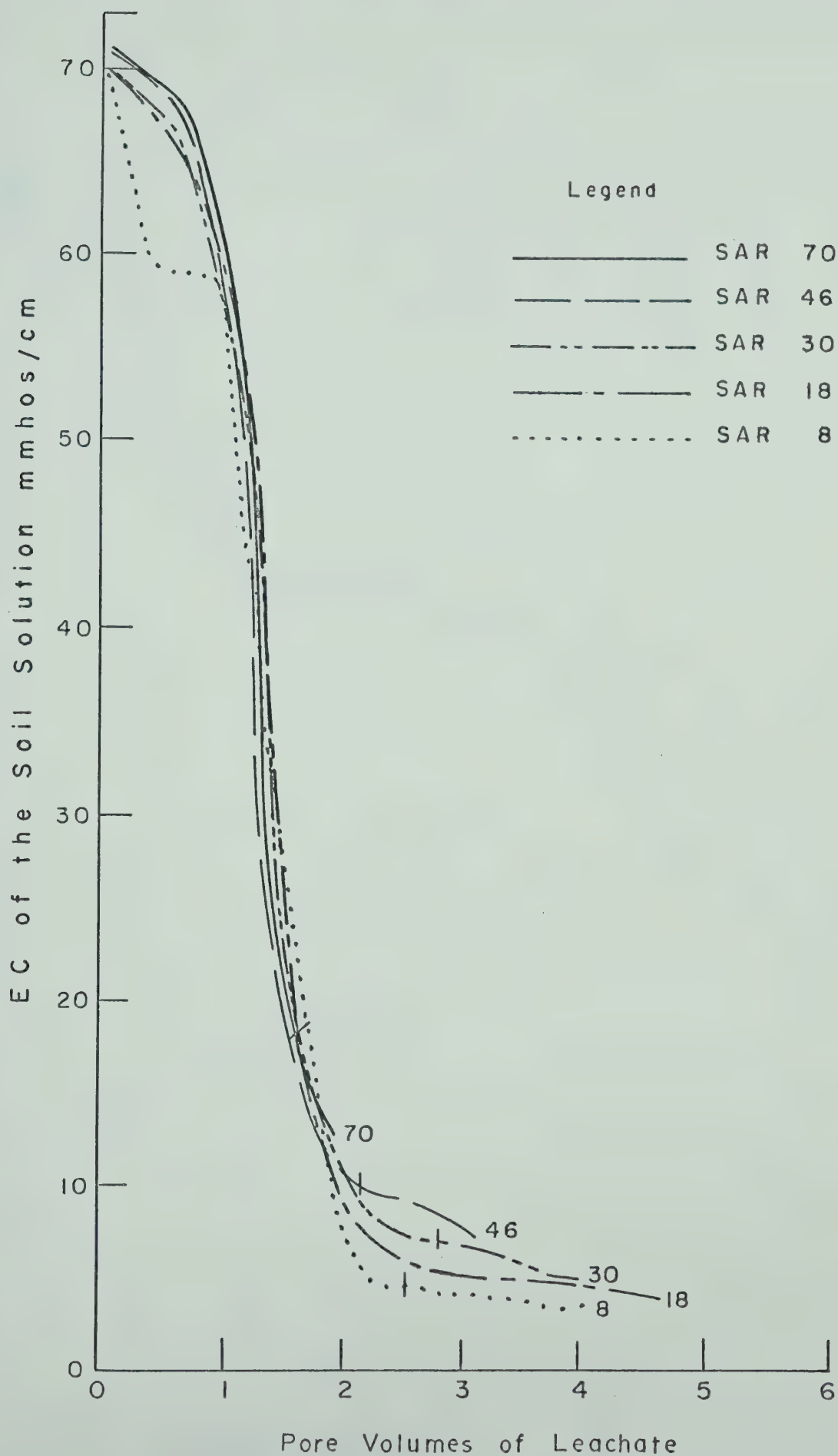


Figure 30. EC values of the leachates from 3 - 1 meq/L leachants at various SAR values.

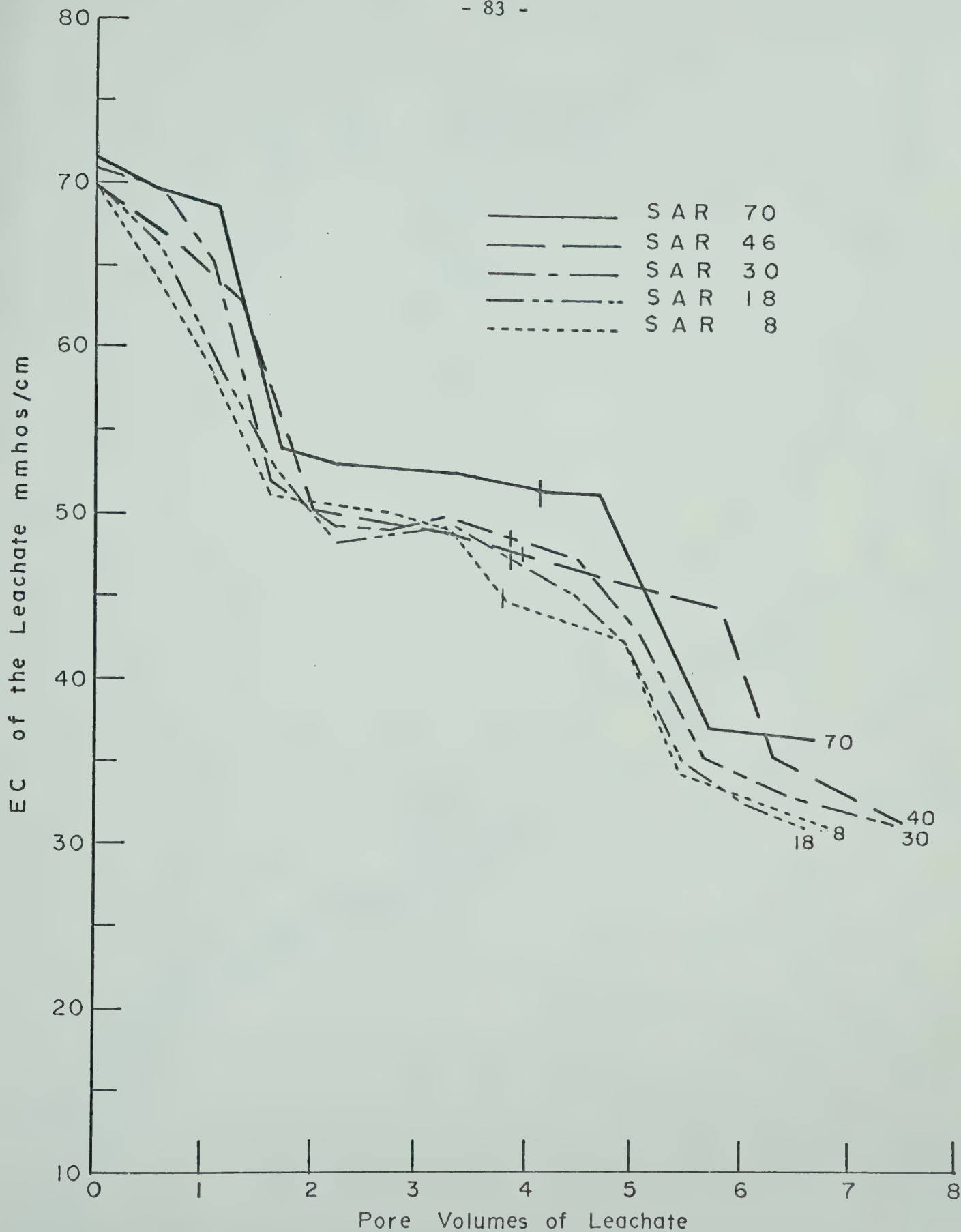


Figure 31. EC values of the leachates from 500 - 300 meq/L leachants at various SAR values.

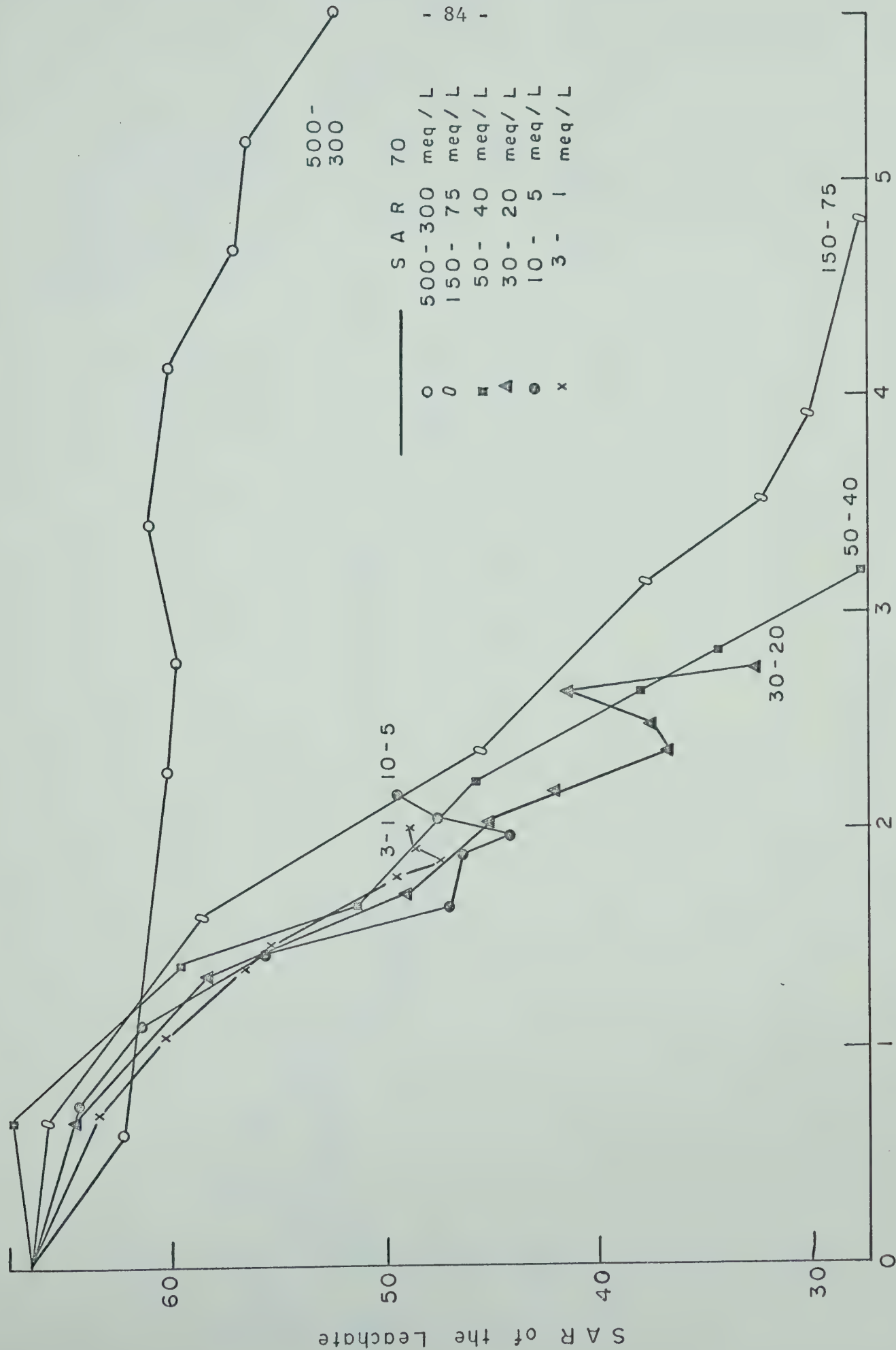


Figure 32. SAR values of the leachates from SAR 70 leachants at various concentrations.

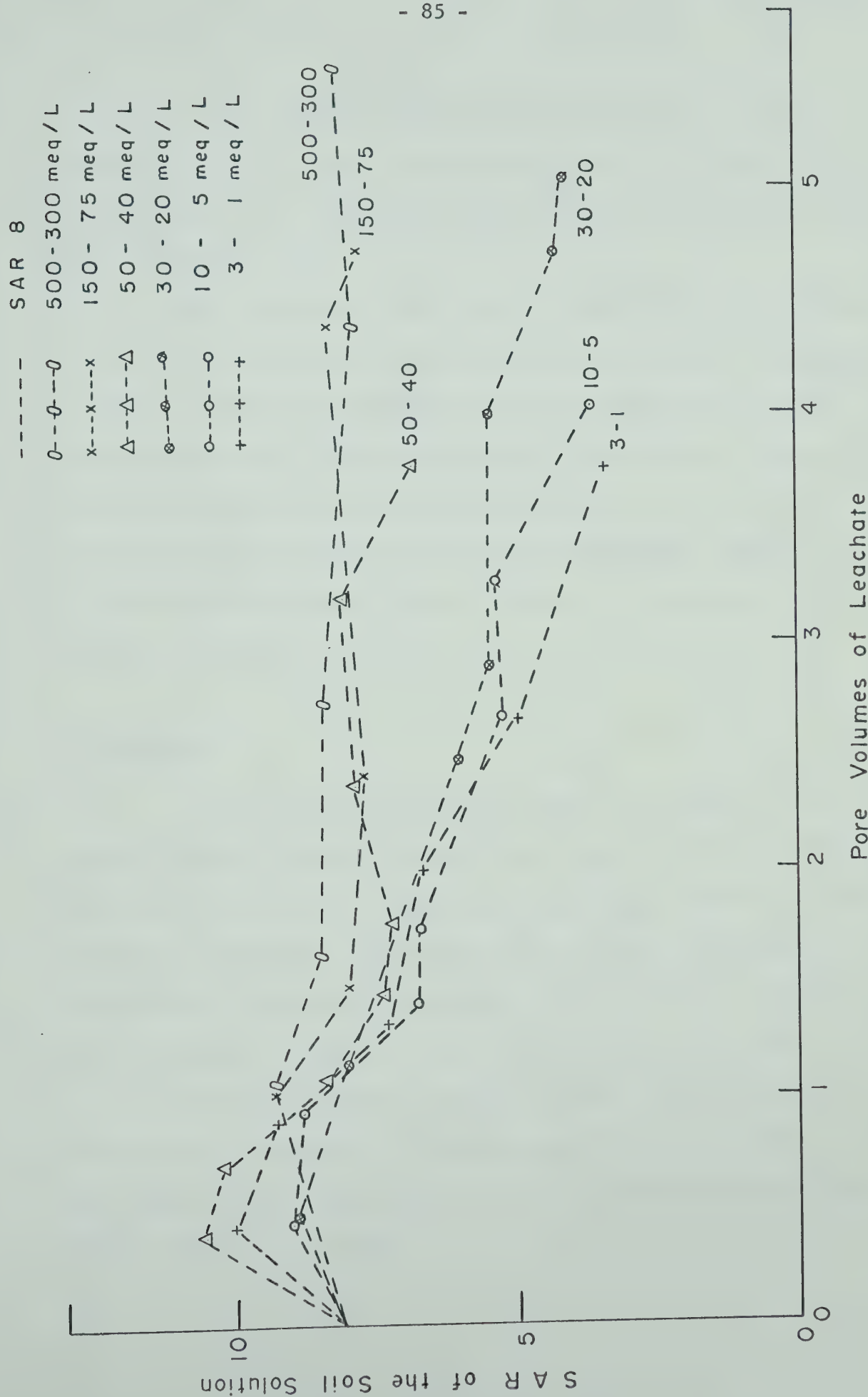


Figure 33. SAR values of the leachates from SAR 8 leachants at various concentrations.

been caused by the increased solubility of CaSO_4 of the soil upon leaching with a low EC and/or high SAR solution. On the other hand the low SAR and high EC leachants obtained equilibrium for their SAR's fairly soon (Figure 33).

These results show that the EC and SAR of the soil solution declined in as many different ways as there were different leachants. In some cases the routes followed crossed one another and formed an alternative route for the desalinization to a particular salinity level. On Figure 34 (see insert) most of the routes which could be used for the desalinization of the original soil are indicated. The choice of the route depends on purely economic factors to be considered in the following sections.

2. Amendments

The total cost of artificial reclamation consisted of the combined charges of water, amendment, and labour. Of these, water and labour were fixed costs and constituted only a small fraction. On the contrary, the amendments formed the major portion of the total cost and could vary considerably depending on the kind of salt chosen. To select a salt and minimize its cost, a leaching test was set up.

Figure 35 presents the EC and SAR data of the leachate with respect to the centimeters of leachate passed through the soil. $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ seemed to be the most effective, followed subsequently by $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

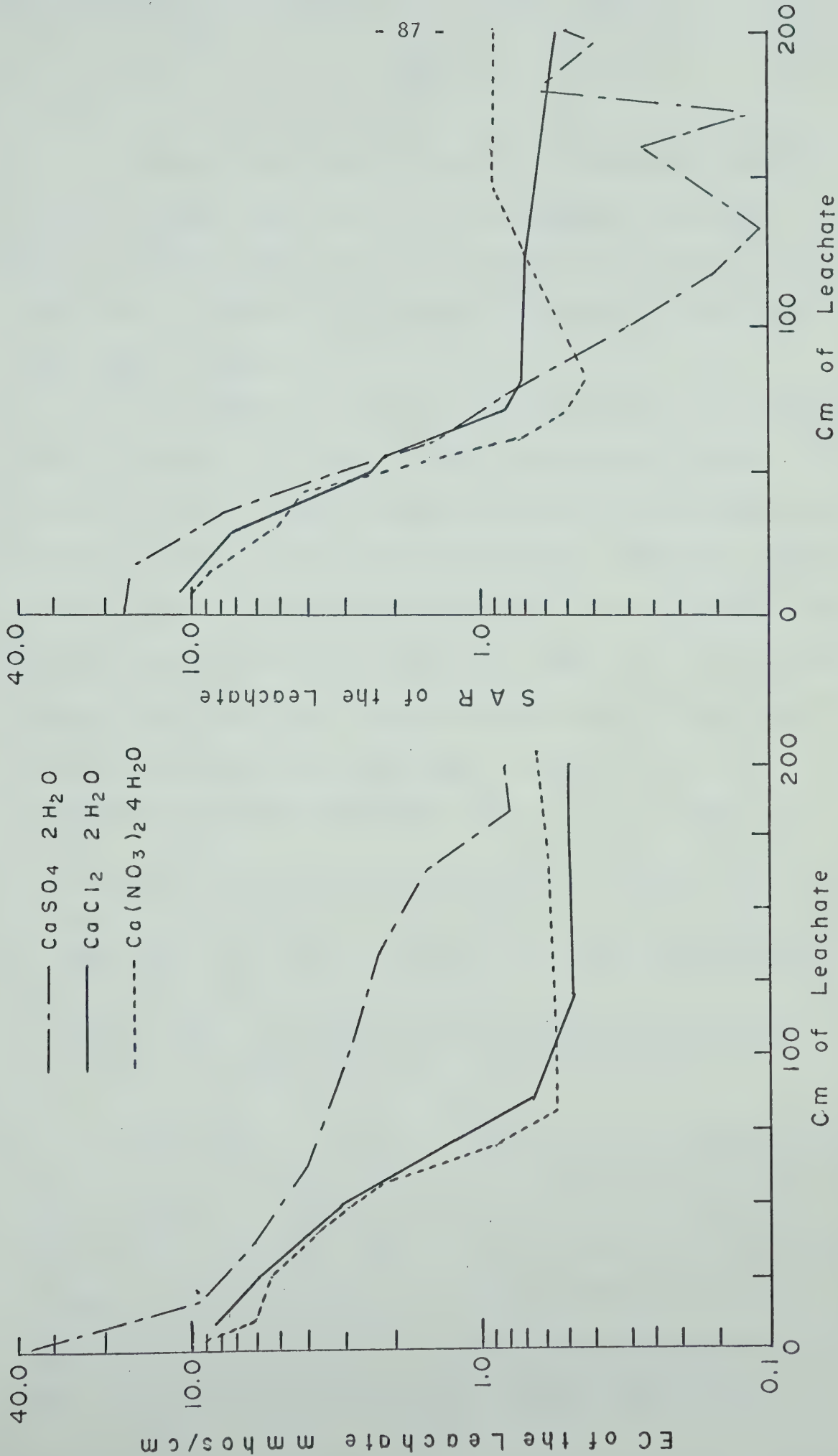


Figure 35. EC and SAR graphs with respect to the centimeters of leachate during the treatment with various amendments.

However, with respect to the cost of reclamation, these efficiency ratings would prove to be quite different from above. Before the desalinization of the soil could be plotted with respect to the cost of reclamation, the charges for amendment, water, and labour had to be found.

(a) Amendments. The amount of salt per ha cm of water was found by converting the amount of salt applied per core surface area to that of a hectare, and by dividing this figure by the number of cm of leachate during which the salt was effective. According to Figure 35, $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ and $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ seemed to be effective for the first 85 cm of leachate while $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ had an effect up to 180 cm. These amounts of salt per ha cm of water were multiplied with the prices of salt as quoted by Van Waters and Rogers Limited, Edmonton, on September 17, 1970. The cost of the salt per ha cm of water was:

$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	30.14 T/ha x \$99.60/T F.O.B. Medicine Hat / 85 cm leachant = \$35.32/ha cm.
---	--

$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	33.15 T/ha x \$45.60/T F.O.B. Medicine Hat / 180 cm leachant = \$8.40/ha cm.
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$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	54.25 T/ha x \$1,506.00/T F.O.B. Medicine Hat / 85 cm leachant = \$961.18/ha cm.
--	--

(b) Water. The cost of water is that for pumping. Pumping from the aquifer cost \$0.167 / ha cm (i.e., \$2.00 / ac ft) and from the creek \$0.125 / ha cm (i.e., \$1.50 / ac ft). However, the need to pump the aquifer in order to lower the watertable and the savings in calcium salt, because of the salts already present in the aquifer water, necessitated the exclusive use of aquifer water in this case.

(c) Labour. The cost of labour per ha cm of water applied is calculated from the cost of labour per hour (\$2.00 / hr), the number of hours of labour required per hectare of levelled land for 2 applications of water (3.0 hr/yr ha), and the centimeters of irrigation water applied per year (30 cm/yr). This came to \$0.20 / ha cm for labour.

From the amounts of water, amendment, and labour and the cost per unit of each, the desalinization curves on a per dollar basis were drawn up (Figure 36). Here $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ appears to be the most economical, with $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ next, and $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ last. Therefore, the recommendation was to use gypsum as much as possible and use $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ only when the limited solubility of gypsum, which is 15 meq/L in the soil solution, would cause a precipitation of gypsum in the soil.

3. Costs and benefits of reclamation

The cost of reclamation for each route on Figure 34 was the combined costs of its sections, or sections of alternative routes which proved to be less expensive. To calculate the cost per section the kind, amount, and unit charge of water, amendment, and labour had to be selected and determined.

(a) Water. The cost of water was again that of pumping, which was \$0.167 / ha cm and \$0.125 / ha cm for well and creek water, respectively. Rather than expressing the amount of leachate on a per centimeter basis, it was more appropriate to do this per pore volume, because the rate of desalinization of a soil correlates more to the number of pore volumes than the number of centimeters solution leached

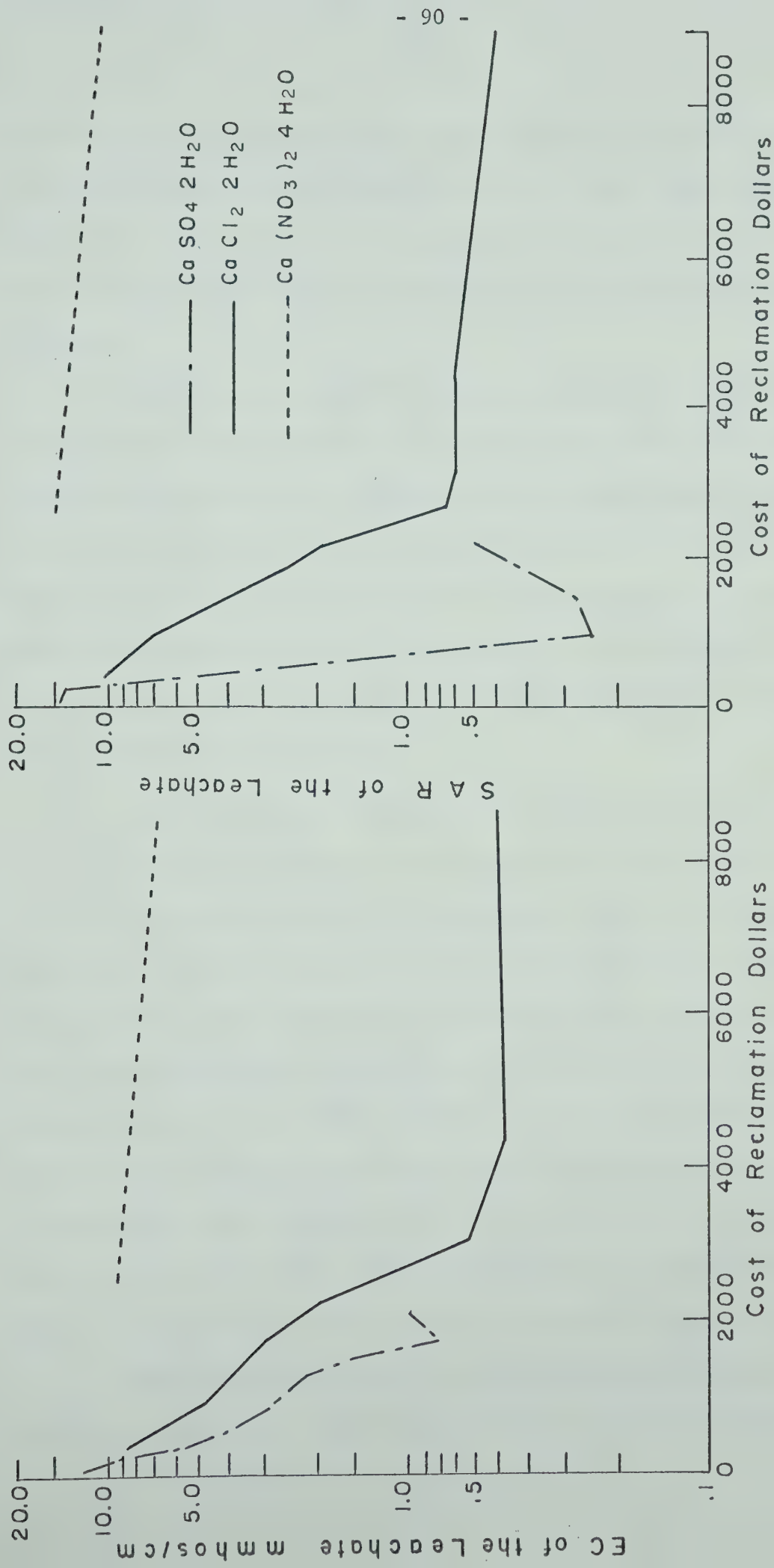


Figure 36. EC and SAR graphs with respect to the cost of reclamation during treatment with various amendments.

through the soil. Assuming that a soil should be reclaimed at least to 60 cm and the porosity being 48 per cent, a pore volume became equivalent to 30 cm water. Consequently the costs for well and creek water were \$5.01 and \$3.75, respectively, per pore volume hectare (Table 8).

Well water was only used when the required Ca and/or Na concentrations of the leachant were above those of the creek water. This allowed for the least saline solutions to use creek water and stay as close as possible to their planned concentrations. However, for the high solutions the savings on Ca and Na already present in the well water and the need for lowering the watertable necessitated the use of well No. 2 water, even though it increased the planned concentration by 1 - 2 mmhos/cm in some cases.

(b) Amendment. The cost for amendments is the investment of Ca and/or Na salts needed to bring the creek or well water up to the required concentrations of the leachants (Table 8). Additional calcium was required though, to replace the calcium that precipitated out as gypsum, after calcium salt was added to the creek or well water which already contained sulfate ions. The amount of Ca precipitated was equivalent to the sulfate originally present in the water minus the sulfate that remained dissolved once the solution was made up. The sulfate that remained dissolved in a soil solution is, according to Quirk and Schofield (1958), half that dissolved in a saturated solution which is determined from the solubility constant of gypsum (Table 8).

Even though gypsum was the least expensive amendment, it could not be used here. The reason was that gypsum had already

Table 8. Cost analyses for leaching solutions with SAR 8 - 70

SAR	Total meq/L	Amount required		Water supply	SO ₄ dissolved meq/L	Ca precipitate meq/L	Added		Cost of added		Cost of water \$/ha pore volume	Cost of amendment + water \$/ha pore volume
		Ca meq/L	Na meq/L				Ca meq/L	Na meq/L	Ca \$/ha pore volume	Na \$/ha pore volume		
8	1	.029	.971	Creek	--	--	--	--	--	--	3.75	3.75
	3	.238	2.762	Creek	--	--	--	--	--	--	3.75	3.75
	5	.604	4.396	Creek	--	--	--	--	--	--	3.75	3.75
	10	2.000	8.000	Well No. 2	--	--	--	--	--	--	5.01	5.01
	20	6.067	13.930	Well No. 2	--	--	--	--	--	--	5.01	5.01
	30	11.130	18.870	Well No. 2	35.04	--	--	1.37	--	5.42	5.01	10.43
	40	16.810	23.190	Well No. 2	23.20	--	4.71	5.69	103.30	22.42	5.01	131.70
	50	22.920	27.080	Well No. 2	17.02	--	10.82	9.58	238.10	37.71	5.01	280.80
	75	39.460	35.540	Well No. 2	9.88	2.82	30.18	18.04	663.50	71.23	5.01	739.70
	150	94.890	55.110	Well No. 2	4.11	8.59	91.38	37.61	2,012.00	149.10	5.01	2,166.00
18	300	216.700	83.280	Well No. 2	1.80	10.90	215.50	65.78	4,733.00	260.30	5.01	4,998.00
	500	388.500	111.500	Well No. 2	1.00	11.70	388.10	94.00	8,521.00	371.20	5.01	8,892.00
	800	655.200	144.800	Well No. 2	0.60	12.10	655.20	127.30	14,420.00	503.40	5.01	14,920.00
	1	.006	.994	Creek	--	--	--	--	--	--	3.75	3.75
	3	.054	2.946	Creek	--	--	--	--	--	--	3.75	3.75
	5	.145	4.855	Creek	--	--	--	--	--	--	3.75	3.75
	10	.551	9.449	Well No. 2	--	--	--	--	--	--	5.01	5.01
	20	2.000	18.000	Well No. 2	--	--	--	0.50	--	1.98	5.01	6.99
	30	4.131	25.870	Well No. 2	--	--	--	8.37	--	33.06	5.01	38.07
	40	6.803	33.200	Well No. 2	--	--	--	15.70	--	62.00	5.01	67.01
30	50	9.917	40.080	Well No. 2	--	--	--	22.58	--	89.26	5.01	94.27
	75	19.210	55.790	Well No. 2	20.30	--	7.11	38.29	156.20	151.20	5.01	312.40
	150	55.330	94.670	Well No. 2	7.05	5.65	48.88	77.17	1,073.00	304.80	5.01	1,380.00
	300	146.100	153.900	Well No. 2	2.67	10.03	144.10	136.40	3,164.00	538.60	5.01	3,708.00
	500	285.100	214.900	Well No. 2	1.37	11.33	284.30	197.40	6,244.00	779.80	5.01	7,029.00
	800	512.000	288.000	Well No. 2	0.76	11.94	511.80	270.50	11,240.00	1,068.00	5.01	12,310.00
	1	.002	.998	Creek	--	--	--	--	--	--	3.75	3.75
	3	.020	2.980	Creek	--	--	--	--	--	--	3.75	3.75
	5	.054	4.946	Creek	--	--	--	--	--	--	3.75	3.75
	10	.213	9.787	Well No. 2	--	--	--	--	--	--	5.01	5.01
	20	.818	19.180	Well No. 2	--	--	--	1.68	--	6.64	5.01	11.65
	30	1.771	28.230	Well No. 2	--	--	--	10.73	--	42.38	5.01	47.39

Table 8. (Continued)

SAR	Total meq/L	Amount required		Water supply	SO ₄ dissolved meq/L	Ca precipitate meq/L	Added		Cost of added		Cost of water \$/ha pore volume	Cost of amendment + water \$/ha pore volume
		Ca meq/L	Na meq/L				Ca meq/L	Na meq/L	Ca \$/ha pore volume	Na \$/ha pore volume		
30	40	3.036	36.960	Well No. 2	--	--	--	19.46	--	76.88	5.01	81.89
	50	4.584	45.420	Well No. 2	--	--	--	27.92	--	110.30	5.01	115.30
	75	9.526	65.470	Well No. 2	40.94	--	--	47.97	--	189.50	5.01	194.50
	150	31.307	118.700	Well No. 2	12.46	0.24	19.45	101.20	427.10	399.70	5.01	831.80
	300	94.160	205.800	Well No. 2	4.14	8.56	90.62	188.30	1,990.00	744.00	5.01	2,739.00
	500	200.000	300.000	Well No. 2	1.95	10.75	198.70	282.50	4,362.00	1,116.00	5.01	5,483.00
	800	384.200	415.800	Well No. 2	1.02	11.68	383.80	398.30	8,428.00	1,573.00	5.01	10,010.00
46	1	.001	.999	Creek	--	--	--	--	--	--	3.75	--
	3	.008	2.992	Creek	--	--	--	--	--	--	3.75	--
	5	.023	4.977	Creek	--	--	--	--	--	--	3.75	--
	10	.093	9.907	Well No. 2	--	--	--	--	--	--	5.01	--
	20	.364	19.640	Well No. 2	--	--	--	2.14	--	8.44	5.01	13.45
	30	.806	29.190	Well No. 2	--	--	--	11.69	--	46.19	5.01	51.20
	40	1.408	38.590	Well No. 2	--	--	--	21.09	--	83.31	5.01	88.32
70	50	2.163	47.840	Well No. 2	--	--	--	30.34	--	119.80	5.01	124.80
	75	4.676	70.330	Well No. 2	--	--	--	52.83	--	208.70	5.01	213.70
	150	16.780	133.200	Well No. 2	23.25	--	--	115.70	102.70	457.10	5.01	564.80
	300	56.190	243.800	Well No. 2	6.94	5.76	49.85	226.30	1,095.00	893.90	5.01	1,994.00
	500	129.600	370.400	Well No. 2	3.01	9.69	127.23	352.80	2,794.00	1,393.00	5.01	4,192.00
	800	267.800	532.200	Well No. 2	1.46	11.24	266.90	514.70	5,861.00	2,033.00	5.01	5,866.00
	1	.000	1.000	Creek	--	--	--	--	--	--	3.75	3.75
	3	.004	2.996	Creek	--	--	--	--	--	--	3.75	3.75
	5	.010	4.990	Creek	--	--	--	--	--	--	3.75	3.75
	10	.040	9.960	Well No. 2	--	--	--	--	--	--	5.01	5.01
	20	.161	19.840	Well No. 2	--	--	--	2.34	--	9.24	5.01	14.25
	30	.359	29.640	Well No. 2	--	--	--	12.14	--	47.96	5.01	52.97
	40	.633	39.370	Well No. 2	--	--	--	21.87	--	86.37	5.01	91.38
	50	.981	49.020	Well No. 2	--	--	--	31.52	--	124.50	5.01	129.50
	75	2.165	72.840	Well No. 2	--	--	--	55.34	--	218.60	5.01	223.60
	150	8.206	141.800	Well No. 2	--	--	--	124.30	--	491.00	5.01	496.00
	300	29.800	270.200	Well No. 2	13.09	--	17.70	252.70	388.70	998.20	5.01	1,392.00
	500	74.050	425.900	Well No. 2	5.27	7.43	69.38	408.45	1,524.00	1,613.00	5.01	3,142.00
	800	164.700	635.300	Well No. 2	2.37	10.33	163.00	617.80	3,578.00	2,440.00	5.01	6,024.00

precipitated from the highly saline Ca-rich leachants because of the sulfate present in the creek and well water. The less saline leachants received so much Ca from the 51 T CaSO_4 per 30 ha cm in the soil that it maintained the Ca content of the effluent 3 to 4 times above that of the leachant (Figure 32), thus causing any added gypsum to be ineffective. Consequently, $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ was used to supply the Ca amendment. For a Na salt, NaCl was used. The cost for increasing the Ca and Na content of the leachant proved to be \$21.96 and \$3.95, respectively, per pore volume hectare. This then resulted in the "cost of added Ca and Na" which was added on to that of water (Table 8).

(c) Labour. Unlike the other two costs, that of labour could not be expressed on a per pore volume basis. The variety of percolation rates, resulting from the leaching with different leachants, required various lengths of time to complete the irrigation. Consequently, the cost of labour was expressed on a per day hectare basis. During each irrigation of approximately 250 hours, 100.4 hectares were irrigated. This was about 10 hectares per day. Assuming 1.5 hours labour per levelled hectare for resetting and a wage of \$2.00 per hour, the cost for labour became \$3.00 / ha day.

From the amounts of water, amendment, and labour, and from the unit charge of each, the total cost for each section of a route was determined (Figure 34). Table 9 presents the minimum total cost for each route which consists of the combined cost of all sections of this particular route, or sections of an alternative route, if these proved to be less expensive. In general, the cost of reclamation

Table 9. Cost and benefit analysis of reclamation

	Revenue \$/ha	Cost of reclamation \$/ha	Net profit \$/ha
SAR 8 - 1	320	520	
5	320	540	
20	310	570	
40	290	400	
75	-30	--	
300	-90	--	
SAR 18 - 1	320	460	
5	320	430	
20	310	400	
40	250	640	
75	-200	1,620	
300	-260	--	
SAR 30 - 1	320	330	
5	320	360	
20	290	330	
40	260	540	
75	20	960	
300	-140	--	
SAR 46 - 1	310	180	130
5	310	210	100
20	290	290	0
40	270	210	60
75	30	690	
300	-140	--	
SAR 70 - 1	200	150	50
5	270	170	100
20	200	210	
40	90	240	
75	90	690	
300	-210	--	

increases with SAR and EC indicating that amendments constituted the major portion of the cost.

From the difference between the "extra crop revenues", and the minimum total costs, the profits resulting from the artificial reclamation were calculated (Table 9). The maximum profit of \$130 / ha was attained using route SAR 46, 3 - 1 mmhos/cm most of the time. Only from SAR 33.6, EC 11.5 mmhos/cm to SAR 30.7, EC 8.8 mmhos/cm was a solution SAR 46 with 5 mmhos/cm used. Consequently, the economic study indicated route SAR 46, EC 3 - 1 mmhos/cm and end point SAR 26, EC 7.5 mmhos/cm as the desired route for an artificial reclamation process of the original saline-sodic soil.

SUMMARY AND CONCLUSIONS

Chemical and physical analyses indicated a resalinization and deterioration of the basins while the border strips are rapidly freed from their salts. In general, the SAR dropped in both the basins and the border strips while the EC dropped 5.5 per cent per year on the border strips but rose 4.9 per cent per year in the basins. Simultaneously, the basins showed a deterioration in HC and the greatest lack of uniformity for the rate of resalinization which, however, was directed in such a way that it would increase the uniformity of salt content between the up and downstream regions of the basins.

The determination of the "area of stable permeability" for our soil revealed several important facts. First of all, upon leaching with the highly saline 800 meq/L solutions, a positive correlation between the SAR of the leachant and the HC of the soil appeared, leachants with low SAR's producing low HC's. The opposite was expected. An illuviation of Na into the bottom portion of the profile, causing there an irreversible reduction in HC, was proven with some success to be the causative factor.

As a second point, the "threshold" concentrations, which established the boundaries of the "area of stable permeability", ranged between 300 and 200 meq/L and proved to be 10 times larger than those found by Graveland (1960) for Alberta Solonetzic soils. The "jump-off" concentrations cast doubt rather than confirm the exact delineation of the "area of stable permeability". At low SAR's, the "jump-off" and "threshold" concentrations were in close proximity to each other but

at high SAR values they deviated substantially. Nevertheless, the "area of stable permeability" was defined accurately enough to show that the chemistry of the original soil was inside, and that of the well and creek waters outside, the "stable areas".

The subsequent economic study embraced greenhouse, leaching, and amendment studies. The greenhouse experiment showed a delayed and reduced germination for alfalfa and barley at high EC and SAR values. Yields of barley and alfalfa decreased with increased salinity but increased with high SAR's. Top yields of barley were obtained at SAR = 4.2 and EC = 4.64 mmhos/cm, while top yields of alfalfa were reached at SAR = 19.8 and EC = 7.85 mmhos/cm.

The leaching study indicated that only the leachants with a low SAR and a high EC reached an equilibration point between leachant and leachate. In contrast, the leachants with low EC and high SAR values maintained leachates with EC's and SAR's above and below, respectively, the expected equilibrium values due to the continuous solvation of gypsum in the soil and the reduced eluviation of salts.

The amendment study indicated that $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ was the most efficient amendment with respect to pore volumes of leachate while $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ proved to be next and gypsum last. However, the low solubility of gypsum necessitated the exclusive use of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$.

The economic study indicated the most efficient leachants, the end point, and the net profit of the most efficient method of artificial reclamation. The most efficient leachants had SAR 46 and the concentrations of 3 and 1 meq/L, except for the part between

SAR 33.6, EC 11.5 mmhos/cm and SAR 30.7, EC 8.8 mmhos/cm when the leachant with SAR 46 and EC 5 mmhos/cm was used. The end point of reclamation was SAR 4.4 and EC 7.6 mmhos/cm; its net profit was \$130 / ha. The three leachants with SAR 46 and EC's of 5, 3, and 1 meq/L were located on Figure 24 outside the "area of stable permeability", and as such the hypothesis that the concentration and composition of the most economical leachant was located inside the "stable area" was disproven.

In conclusion, the study indicated that the correct solution was used on lot 9, Upper "V", to achieve a very economical reclamation. Nevertheless, the net profits could have been raised by another \$130 / ha if the lot had initially been artificially reclaimed to SAR 4.4 and EC 7.6 mmhos/cm. Therefore the recommendation for future reclamation of the remaining saline areas on the Upper "V" is that the soil be leached with a substantial amount of creek or well water immediately after proper drainage is installed.

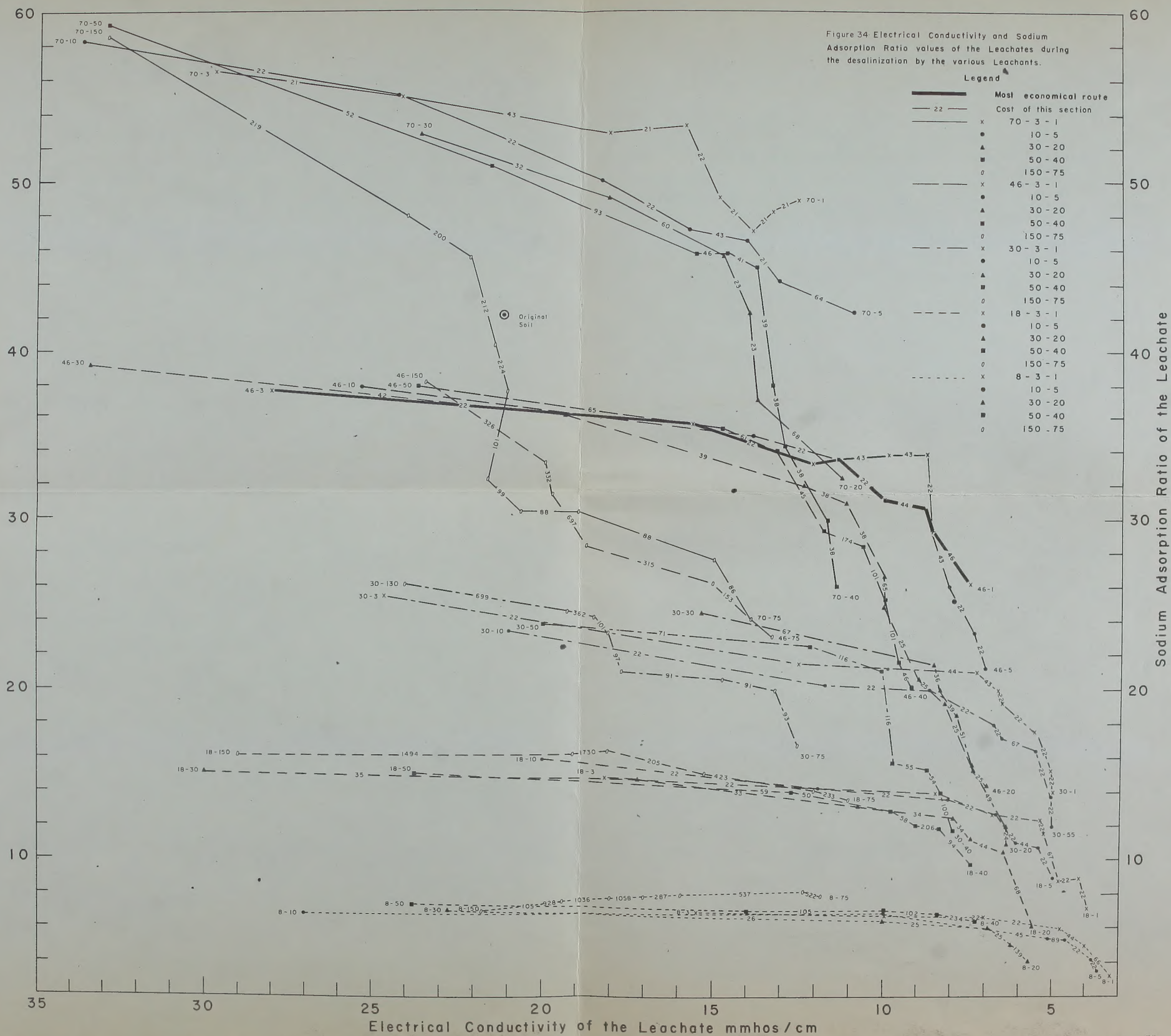
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